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CONVOY PROTECTION UNDER MULTI-THREAT SCENARIO

by

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June 2017

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13. ABSTRACT (maximum 200 words)

Convoy screening has long been studied and practiced to minimize losses of ships supplying forward battle areas. Today, the threat of surface and subsurface platforms equipped with torpedoes and anti-ship cruise missiles (ASCMs) requires reevaluation of the best protection measures taken by warships, aircraft, and unmanned systems to screen convoys.

This research used agent-based simulation to develop and analyze the effectiveness of 18 models based on two basic screening methods: zone defense and close escort. Variants were developed based on stationing and type of combatant platforms—manned and unmanned. They were tested for robustness against two Red submarine approach tactics based on weapon priority and various acoustic conditions. The study determined the optimum weapon/sensor capabilities of combatant platforms for effective protection. We showed that layered defense in the outer screen is the most robust and effective defensive model against any Red weapon priority tactic and in any acoustic condition. A model with ASW helicopters in the intermediate screen was found to be the most effective against submarines with torpedo as priority weapon. Models with ASW helicopters or MDUSVs and two DDGs in the outer screen, however, were found to provide better defense against submarines with ASCM as priority weapon.

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CONVOY PROTECTION UNDER MULTI-THREAT SCENARIO

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Convoy screening has long been studied and practiced to minimize losses of ships supplying forward battle areas. Today, the threat of surface and subsurface platforms equipped with torpedoes and anti-ship cruise missiles (ASCMs) requires reevaluation of the best protection measures taken by warships, aircraft, and unmanned systems to screen convoys.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	anti-air warfare
ACTUV	ASW Continuous Trail Unmanned Vehicle
ANOVA	analysis of variance
AOO	area of operation
AOR	area of responsibility
ASCM	anti-ship cruise missile
ASM	air to surface missile
ASW	anti-submarine warfare
C/Def	coastal defense
DARPA	Defense Advanced Research Projects Agency
DDG	guided missile destroyer
DES	discrete event simulation
DMM	disposition mission model
DoE	design of experiment
DP	design point
DTA	Defense Technology Agency
ESM	electronic support measure
FC	fire control
FFG	guided missile frigate
FPB	fast patrol boat
HVU	high value unit
IR	intelligence and reconnaissance
ISR	intelligence surveillance and reconnaissance
LGB	Laser guided bomb
LLSuA	limiting line of submerged approach
LLA	limiting line of approach
LOA	line of advance
MALE	medium altitude long endurance
MANA	Map Awareness Non-Uniform Automata
MDUSV	Medium Displacement Unmanned Surface Vessel

MLA	mean line of advance
MOE	measure of effectiveness
MOP	measure of performance
NM	nautical mile
NOLH	nearly orthogonal Latin hypercube
OSM	orchestrated simulation through modeling
PLAN	People Liberation Army (Navy)
RedSubTact	Red submarine tactic
SAM	surface-to-air missile
SAU	search and attack unit
SLOCS	sea lines of communications
SoA	speed of advance
SSKP	single shot kill probability
SSK	conventional attack submarine
SSN	nuclear attack submarine
TALON	Towed Airborne Lift of Naval Systems
TERN	Tactically Exploited Reconnaissance Node
TSR	Tactical sonar range
UAV	unmanned aerial vehicle
USV	unmanned surface vessel

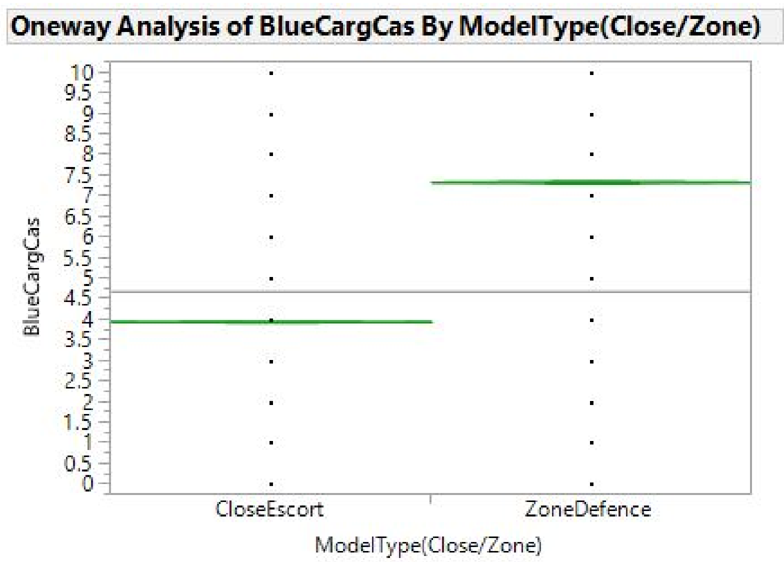
EXECUTIVE SUMMARY

Sustained logistics determine the war stamina of a force against near-peer competitors. Therefore, war logistics are considered vital and offer the most lucrative target for an adversary. If the U.S. Navy is to transfer vital supplies to its forward battle areas in a full combat situation, effective defensive measures to minimize the expected losses of supply ships must be found to counter a new threat from surface and subsurface platforms, each equipped with torpedoes and anti-ship cruise missiles (ASCMs). Convoy operations proved to be effective in both world wars against the threat of German U-boats capable of launching torpedoes only. Modern submarines, however, are now capable of launching long-range ASCMs (in addition to the ever-more lethal torpedoes) while remaining underwater. Additionally, surface combatants with good self-defense are capable of attacking a convoy with long-range ASCMs. The two platforms combined against a convoy is a much more lethal threat, requiring defensive enhancement and more planning.

This research utilized the agent-based simulation software MANA to analyze the effectiveness of various tactics to protect convoys. A total of 18 models were developed based on stationing and types of combatant platforms. The models are based upon two convoy screening methods: zone defense in which defensive forces search ahead of the convoy's track to create a clear transit path and close escort operations providing a protective shield for the convoy against anti-ship cruise missile (ASCM) and torpedo attacks. The Blue combatant platforms included guided missile destroyers (DDGs), nuclear attack submarines (SSNs), antisubmarine warfare (ASW) helicopters, Medium Displacement Unmanned Surface Vehicles (MDUSVs), and Tactically Exploited Reconnaissance Node unmanned air vehicles (TERNs). Additionally, these models were tested against two Red submarine weapon employment tactics (i.e., standing off from the convoy to first employ ASCMs and then closing for a torpedo attack, and closing on the convoy for a torpedo attack and then launching ASCMs). The first tactic carries less risk for the submarine, but employs the lesser effective weapon against a large merchant ship. We looked for the most robust solution for convoy protection against any Red submarine

weapon employment tactic in any acoustic condition. Additionally, the study determined the optimum weapon and sensor capabilities of combatant platforms for effective convoy protection against the modern threat.

The close escort model outperformed the zone defense model in all the variants. With a convoy size of 10, expected cargo ship casualties were 3.95 [3.937, 3.972] in the close escort model and 7.35 [7.317, 7.382] in the zone defense model, indicating the close escort model was almost twice as effective as the zone defense model (Figure 1).



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
CloseEscort	216720	3.95473	0.00876	3.9376	3.9719
ZoneDefence	61920	7.34952	0.01639	7.3174	7.3816

Std Error uses a pooled estimate of error variance

Figure 1. Losses of convoy ships in zone defense and close escort models.

In 14 variants of the close escort model, the variant with two ASW helicopters in the intermediate screen and five DDGs in the close escort role conceded minimum expected convoy losses (2.62 [2.572, 2.741]) when the Red submarine’s weapon employment priority was torpedo attack first or against a Red submarine having torpedo as its only weapon. It was almost ineffective against a Red submarine attacking first with ASCMs, however. In this case, defensive screens with helicopters or MDUSVs in the

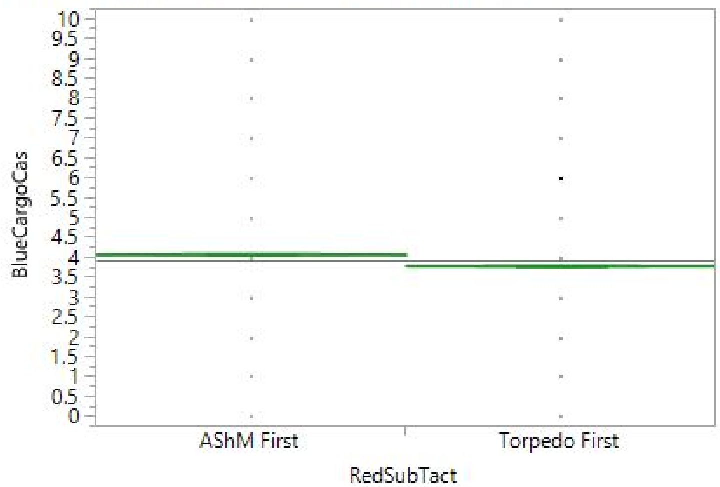
outer screen were found to be more effective with low expected losses of 3.194 [3.106, 3.282] and 3.269 [3.181, 3.357], respectively.

The convoy incurred most losses to Red submarines instead of Red surface ships. Since unmanned aerial TERNs were used for surface surveillance only against Red DDGs, their inclusion was insignificant in preventing convoy loss with current Blue anti-ship missile capabilities. MDUSVs were found to be as effective as the helicopters and the models comparing them were statistically insignificant in performance.

Regression, partition tree, and individual factor analysis were conducted for sensitivity of the models. The factors for sensitivity analysis included weapon and sensor ranges and accuracies as well as Red submarine weapon priority tactics. Enhancing Blue air defense capabilities was found to be more effective than enhancing underwater defense capabilities until the minimum requirements to defeat anti-ship cruise missiles were met. These air defense capabilities included radar range and inventory of surface-to-air missiles. This implies that convoy defense is now more an air defense mission than antisubmarine warfare mission. It also suggests that escorts be of high caliber combatants.

Red submarines were found to be more effective when they employed ASCM as their priority weapon against the Blue convoy. On average, the Blue convoy lost 4.1 [4.078, 4.125] cargo ships when the submarine employed ASCM first and 3.8 [3.784, 3.832] otherwise (Figure 2).

Oneway Analysis of BlueCargoCas By RedSubTact



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
AShM First	108360	4.10171	0.01214	4.0779	4.1255
Torpedo First	108360	3.80776	0.01214	3.7840	3.8316

Std Error uses a pooled estimate of error variance

Figure 2. Casualties of Blue cargo vessels vs Red submarine weapon employment priority.

This small difference keeps the question open, as the simulation assumed the two weapons had similar lethality, which may not be the case. A torpedo hit is sufficient to sink a large ship, whereas it can sustain multiple ASCM shots and remain afloat. On the other hand, it was found that by firing ASCMs first, the submarine disclosed its position to the Blue combatants and was killed more frequently, thereby having fewer opportunities to close for torpedo attack than when it used torpedo as the priority weapon. Submarine concealment factor, reflecting its quietness and/or various acoustic conditions, was also analyzed in sensitivity analysis. When a Red attack submarine's quietness or acoustic conditions allowed it to approach with small chance of detection, a torpedo attack first tactic benefitted the submarine. The models having two MDUSVs along with two DDGs in the outer screen and five DDGs in the inner screen were more robust and effective against quieter submarines and/or in difficult acoustic conditions. The models containing ASW helicopters were outperformed by those in which they were replaced by MDUSVs when the convoy was faced with a threat comprising quieter submarines and/or in difficult acoustic conditions.

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I. INTRODUCTION

A. OVERVIEW

In today's interdependent world, the majority of trade between countries is carried on and over the sea. Sea transport provides the main source of transferring cargo and fuel around the world on established sea lines of communications (SLOCS) and accounts for over 90% of world trade (International Chamber of Shipping, n.d.). Additionally, sustained military operations, especially naval operations, require continuous supply of weapons, fuel and personnel across the sea. These tenets being equally known to potential adversaries, they can plan to target the merchant ships voyaging on SLOCS that carry vital supplies to the battle forces. To provide protection to these merchant ships and/or high value units (HVU) against an enemy, convoy operations are carried out. The success or failure of convoy operations may have impacts ranging from the tactical level to the strategic level. The use of convoys to gain defensive advantage has been reaffirmed in history, especially in World War I and World War II. In World War II, the allied merchant ships were faced with the threat of German U-boats in the Atlantic Ocean. Convoy protection not only significantly reduced the casualties to these merchant ships but sank the U-boats at a rate that forced Germany to abandon attacks on Allied convoys (U.S. Navy OEG Report No.51, 1946).

In light of the above, protection of sea lines of communications (SLOCS) and convoy operations are among the core tasks of any naval force. These are conducted under various scenarios including threats from enemy air, surface and subsurface platforms or a combination of any or all of them. Convoy protection against subsurface torpedo attack has been thoroughly analyzed since the 2nd World War. With the advent of new weapon and sensor technologies and development of new type of sea platforms (unmanned systems like Medium Displacement Unmanned Surface Vessel (MDUSV) and Tactically Exploited Reconnaissance Node (TERN)), however, the dynamic of this warfare has significantly changed. In addition to torpedoes, modern submarines are equipped with long-range anti-ship cruise missiles (ASCM), which they can launch while remaining underwater. These missiles have sophisticated technologies, making them

difficult to detect and destroy. This capability has made the submarine more lethal in naval warfare and its effectiveness against convoys has significantly increased. Accordingly, most efforts in convoy protection tactics are meant to deal with the subsurface threats. Now that surface combatants and air platforms are equipped with high definition radars, ASCM and strong self-defense systems, they add new dimensions to threaten a convoy. Thus, the convoy protection operations need more embellishment and planning against these modern threats.

It is a highly challenging task for surface ships to protect a convoy against multi-dimension threats (submarine combined with surface and/or air threat). In addition to effective tactics, they need good material capabilities both in terms of underwater sensors (sonars) and weapons (torpedoes, depth charges, noise makers, etc.) as well as anti-air capabilities against the air threat such as advanced surface-to-air missiles and high definition radars). Additionally, they need to be appropriately placed with respect to the convoy so that any subsurface threat is timely detected and neutralized or at least its access to the convoy is denied. Therefore, it merits a well-defined methodology and allocation of appropriate resources to ensure protection of a convoy. Various convoy protection instructions are available in maritime tactical publications. These range from stationing surface ships and ASW helicopters around a HVU or convoy in close and/or distant area defense to zone defense stations. These instructions, however, are general guidelines and need further elaboration prior to implementation in a particular scenario. Additionally, they are not up-to-date with the new technologies and developments in naval warfare.

For an adversary’s submarine, missile launching capability provides different tactic options against the convoy. A heavy weight torpedo is considered the most lethal weapon in naval warfare, as one underwater torpedo hit is mostly sufficient to sink a large convoy sea-borne platform. The same convoy ship, however, may take more than one missile hit and still be able to maintain its seaworthiness. In this regard, it is quite intuitive to say that priority of weapon employment for a submarine is torpedo over missile. Yet, there is an additional risk of detection associated with closing the convoy to gain a torpedo launching position as compared to a longer-range missile launch. On the

other hand, if the submarine opts for carrying out missile attack first and then closes for a torpedo attack, it may expose its position early and increase its probability of being neutralized before carrying out the more lethal torpedo attack. This in turn brings a tradeoff between the two tactical options for a submarine.

B. BACKGROUND

In World War II, the Allies' forces supplied much needed war material to their embattled ally Russia in the northern European theater (Vego 2015). These convoys faced the threat of German U-boats and Luftwaffe bombers. A convoy codenamed PQ17 sailed from Hvalfjord, Iceland on June 27, 1942, for the port of Arkhangelsk, Soviet Union. It was located by the German forces on July 01, 1942, and shadowed continuously. Based upon intelligence, the Allied close escorts and cruisers were ordered by the British commander to counter the incoming threat of German surface combatants and disperse the convoy. The convoy ships thus left on their own were attacked by the German U-boats and Luftwaffe planes. The convoy lost 24 of 35 ships, which forced the Allies to abandon any further adventure over the Arctic. PQ17's disastrous outcome made the defense of convoys a major naval operation for Allied forces throughout the war. They revisited their convoy operations plan and dramatically improved performance, losing only 4 convoy ships in the next two years (Milan 2015). This highlights the importance of comprehensive planning and execution of convoy operations against a specific threat.

This study addressed the problem of protecting a small convoy (10 cargo vessels without self-defense) against multiple threats (surface, subsurface and ASCM) in a full combat scenario. The Blue convoy was planned to transfer vital supplies on the open ocean over a distance of 500 nautical miles (NM) from a main supply base to a forward station. Main assumptions of the study included following:

1. Full combat environment (i.e., unrestricted rules of engagement)
2. Blue had achieved air superiority over the area of operation (AOO) as shown in Figure 1. This assumption scoped out the aircraft threat from Red force.
3. The whole battlefield for the scenario was 500 × 500 NM.

4. Blue had established a land-based surface surveillance up to 100 NM and coastal defense against all type of threats up to 50 NM around the main supply base and forward station. Therefore, the threat from submarine attack was restricted to 400 × 500 NM and from surface platforms to 300 × 500 NM. The Red platforms were expected to be patrolling the areas in barrier search pattern.

5. There was perfect sharing of knowledge among the surface and/or air units of both forces.

6. There was no coordination between units for target and weapon assignment. A unit fired on a target whenever that target came within the unit's weapon's range.

7. The convoy did not maneuver to avoid submarine contacts (simulation software limitation).

8. Zone defense was established 14 hours in advance of the planned convoy transit.

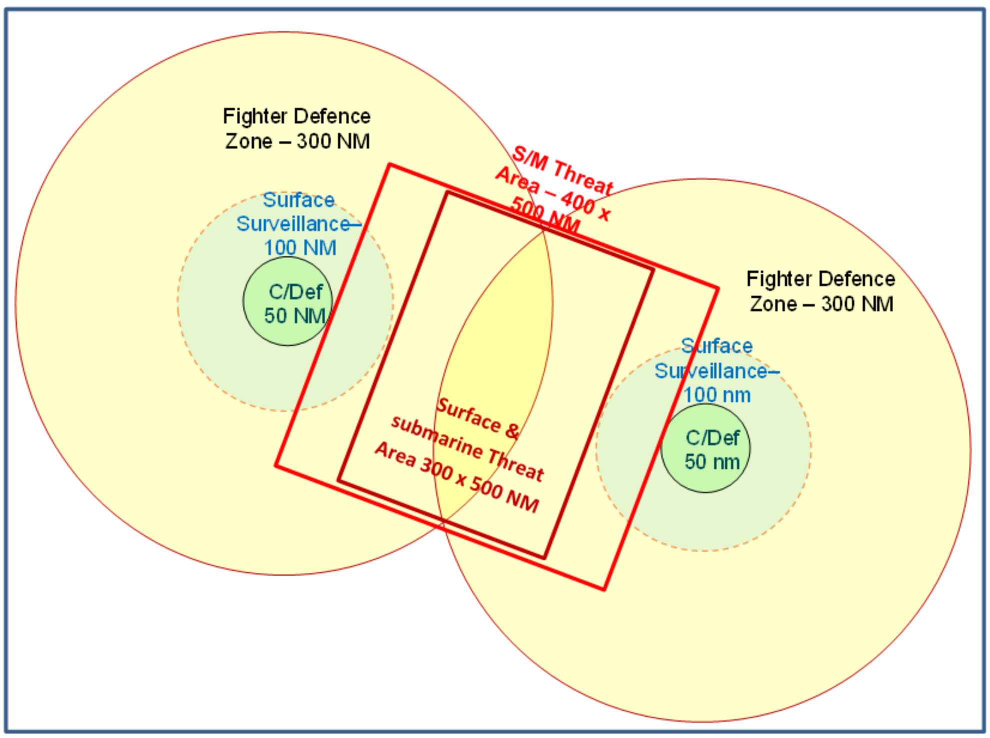


Figure 1. Blue Defense Zones: Area defense is well established over the main supply base and forward base. Threat to convoy is from Red surface and submarine platforms in a 400 × 500 NM box.

Different employment options in terms of tactics and type of platforms were available. The Blue force could employ surface ships, submarines and air platforms (ASW helicopters) or a combination of all or any of them. It also had the option of employing unmanned systems like a Medium Displacement Unmanned Surface Vessel (MDUSV) with Towed Airborne Lift of Naval Systems (TALON) and a Tactically Exploited Reconnaissance Node (TERN) (described in detail in Chapter III).

This thesis analyzed various tactical employment options for surface ships and unmanned systems to provide the most robust and effective convoy defense against a multi-domain threat. It analyzed the effects of weapons and sensors configurations of the escorts in close and distant support to establish the minimum capabilities of the escorts for successful convoy operations. It also provided insight into the effective employment of unmanned systems mentioned above to act synergistically with the manned systems. Additionally, it explored the best attack plan of a Red submarine against the convoy, whether to first attack the convoy with torpedo or anti-ship cruise missile.

C. RESEARCH QUESTIONS

The research was guided by the following questions:

1. Is a defensive screen disposition different when defending against a missile firing submarine as opposed to a torpedo-only submarine?
2. What is the most effective employment tactic of surface combatants in convoy operations in multi-threat environments?
3. What is the most robust employment tactic of escorts in convoy operations against various attack tactics of a submarine capable of launching long-range ASCM and torpedoes?
4. What should be the optimum sensor and weapon configuration of escorts to provide effective protection to the convoy?
5. What is the optimum employment plan for MDUSVs with TALON and TERN in a multi-threat environment?
6. What is the best weapon employment tactic (ASCM first or torpedo first) for a Red submarine attacking a convoy protected by escorts?

D. SCOPE OF THE THESIS

This thesis provides insight to the need of revising the convoy protection tactics when faced with multiple threats comprised of submarines and surface ships capable of launching anti-ship cruise missiles. It evaluates the effectiveness of close escort operations versus zone defense in convoy operations. It helps establish the optimum convoy escort capabilities in terms of weapon and sensor ranges and effectiveness. It explores a Red submarine’s tactical choices of attacking the convoy first with a long-range missile followed by closing for a torpedo attack or vice versa.

E. METHODOLOGY

This research uses “Map Aware Non-Uniform Automata Version V” (MANA V) software simulation environment for simulating convoy tactical engagements, and intelligent design of experiment and data analysis, to answer the research questions. MANA is an agent-based simulation software in which constructed virtual entities make decisions stochastically based on sensing their local environment and following programmed defined parameters in response.

The research included building a model for convoy operations under multi-threat environments with long-range subsurface-to-surface missile launch capabilities. A total of 36 scenarios were developed based on configuration and formation of escorts and submarine attack tactics. There were two basic Blue force defense models used in the research: sector screen formation around the convoy and zone defense comprising surface combatants and/or submarines ahead of the convoy. The basic sector screen comprised seven surface escorts in the inner screen only with 10 merchant ships as convoy. A screenshot of the situation in MANA is shown in Figure 2.

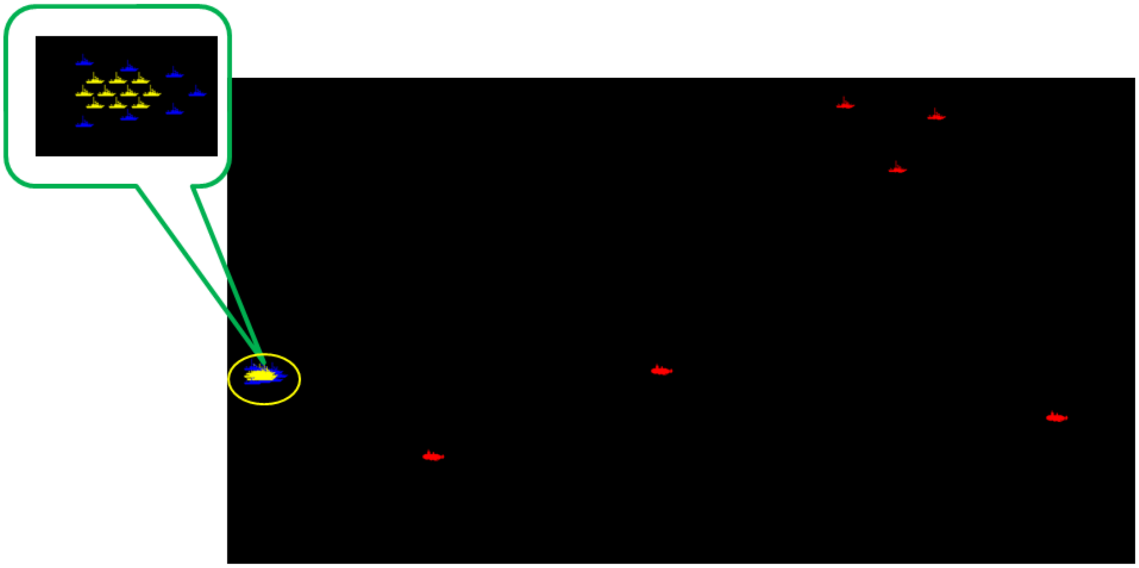


Figure 2. Scenario 1 screenshot of MANA: Close escort model showing seven Blue escorts with the convoy. Three Red submarines and three Red DDGs are patrolling the area of operations.

Twenty-eight scenarios were built, varying the type of platforms including ASW helicopters, MDSUVs with TALON and TERN and putting them in the middle or outer screen against various attacking submarine tactics. The remaining eight scenarios were variants of a zone defense tactic. These scenarios are discussed in detail in Chapter III, "Development of Model." The model was run for different parameter configurations using a design of experiment technique. For design of experiments, we used a combination of full factorial and nearly orthogonal Latin hypercube (NOLH) design spreadsheets. The NOLH provides good space filling and statistical properties with fewer design points than a full factorial effort. The NOLH factors included capabilities of different type of escorts, such as the number of surface-to-air missiles (SAM) on escorts. Blue surface combatants were limited to 7, submarines to 3, MDUSVs to 6 and TERNs to 2.

Sixty runs were made on each design point using a cluster computer configuration, and data was gathered on each run for the number of kill of the cargo vessels and combatants. Statistical techniques were then used to verify the effectiveness of various tactics for convoy protection and answer the research questions

F. CHAPTER OUTLINE

Chapter II covers the literature review and analytical tools used in the study. It also explains the reasons for selecting Map Awareness Non-Uniform Automata (MANA) as the simulation software platform. Chapter III explains the model development, types and attributes of the platforms used therein. It describes all the 36 scenarios along with their major assumptions. Chapter IV briefly describes the factors that are considered significant for affecting the model outcome. It also explains the mapping of scenarios in MANA and design of experiment (DOE). Chapter V shows analysis of the simulation results using various statistical techniques. Chapter VI concludes the thesis report with summary, recommendations and some useful insights for the decision makers. It also mentions room for future work in the area of convoy operations at sea.

II. ANALYTIC TOOLS AND LITERATURE REVIEW

A. DESCRIPTION OF ANALYTIC TOOLS

We considered two simulation software applications for our study: Orchestrated Simulation through Modeling (OSM) and MANA-V. Both are agent-based, but each carries its own benefits and constraints. OSM is under development with on-going updates and its utilization for the study was constrained by time to complete its revisions. It was therefore decided to use MANA-V as it was able to capture almost all the aspects of our model. After development of the model, the DOE was developed according to the acceptable software format. It required a complete mapping of the scenarios and the NOLH design points in MANA. Additionally, we used JMP and R for analysis of the data collected from the simulation runs. The various software applications are described in the following paragraphs:

1. Map Awareness Non-uniform Automata Version V

MANA is agent-based time step simulation software in which model entities are defined as agents. It is developed by the Defense Technology Agency (DTA) of New Zealand for use in military operations analysis (ref. MANA-V Manual) and is used for a wide range of studies at Naval Postgraduate School. These include the master's theses of Unlu (2017) "Effectiveness of unmanned surface vehicles in anti-submarine warfare with the goal of protecting a high value unit," Tsilis (2011) "Counter piracy escort operations in the Gulf of Aden"; Raffetto (2004) "Unmanned aerial vehicle contributions to intelligence, surveillance, and reconnaissance missions for expeditionary operations," Sikandar (2016), "Analysis of protection measures for naval vessels berthed at harbor against terrorist attacks," and Kaya (2016) "Evaluating effectiveness of a frigate in an anti-air warfare (AAW) environment."

In MANA, agents' properties are defined based on capabilities of the model entities and are named accordingly. They act autonomously to sense the environment and react to the events happening there according to user defined personalities, as shown in Figure 3. These personalities may be defined differently for each user-defined trigger

state. Apart from personalities, other properties like agents' speed, concealment, sensors and weapons ranges and accuracies, and whether they are available or not may also be made state dependent. An agent can share its situational awareness picture with its friendly units whose behavior can also be defined based on this inorganic information.

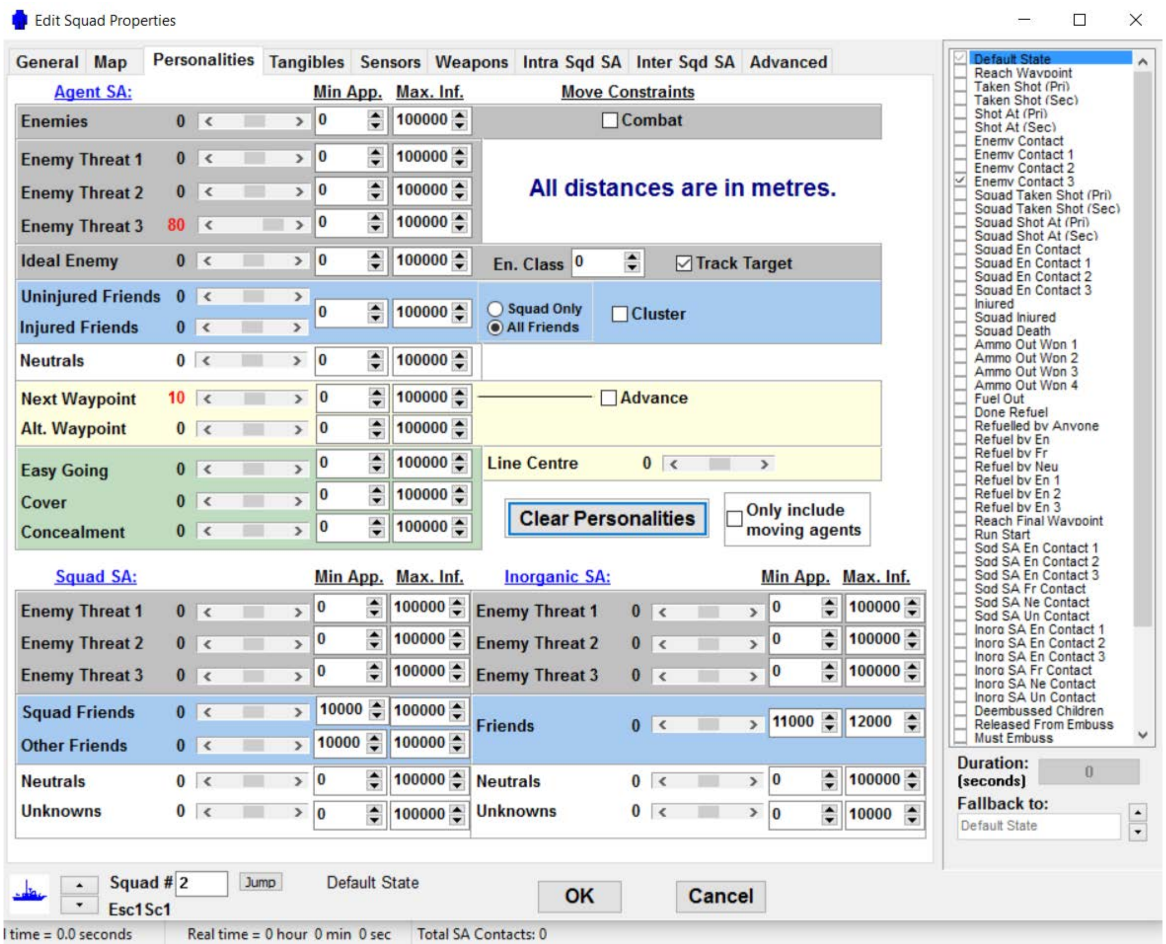
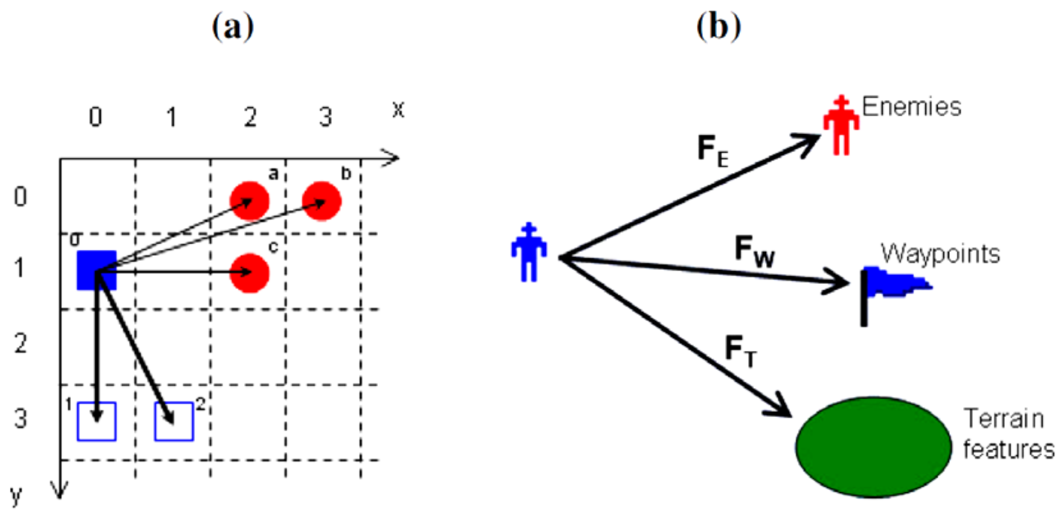


Figure 3. Personality of Squad #2 in default state: MANA window allowing user-defined agent personalities.

In MANA-V, the agents follow a vector-based movement algorithm that provides it an edge over its earlier versions. The earlier versions use grid-based movement algorithms. The difference between the two can be viewed in Figure 4. In grid-based versions, the agents move from one grid square to another based upon their predefined propensities to move towards enemy, neutral or friendly agents. In the vector-based

version, agents calculate their vectors of movement according to their predefined propensities towards friendly, enemy and/or a goal. One can also have different propensities of agent movement towards different class agents within the categories of friendly, enemy and neutral agents. Other advantages of version V include usage of real-world data units for ranges of weapons and sensors, speeds of agents and definition of larger battlefields that can be panned and zoomed.



(a) Shows the cell-based movement of earlier versions 1–4. The solid square represents the present position of a blue agent, whereas the hollow blue squares represent their friends. The red circles represent the enemy agents. The blue agent can move towards the cell containing friendly or enemy agent based on its defined personalities.

(b) Shows that a blue agent calculates its vectors towards the 3 visible objects and moves on the one for which it has high propensity.

Figure 4. Comparison of the MANA-V agent movement with earlier version.

MANA has several limitations with respect to certain scenarios and tactics. It cannot completely capture the real-world characteristics of military entities. It does, however, give good insight into the overall combat outcome. MANA's main benefit is that its wide range of scenarios can be run on a personal computer in a very short time frame and still highlight important factors for Blue and Red forces. Other benefits include its ability to capture the predefined stochastic behavior of agents.

Although MANA is a good tool to simulate models in a short timeframe, it carries constraints on the amount of details a particular problem may demand. Those affecting this study are highlighted here to explain some of the study assumptions.

- Its main board is limited to 540 × 540 NM. Our area of operations was dictated by this limitation, but it did not have any impact on our analysis.
- Dynamic waypoints cannot be assigned to agents, which limits tactical maneuver. This prevented us from modeling any defensive convoy tactical maneuver in response to a submarine contact.
- Speed cannot be assigned to any missile or torpedo (weapons) nor can any defense be assigned against them except their probability of hit. To incorporate the speed to a weapon and defense against it, we defined a child agent with the weapon's attributes. This child agent was released when the parent agent wanted to fire the associated weapon, which proceeded towards the target with its own guidance. It could be detected by the target and killed, thereby representing the defense against it.

2. JMP Software

JMP is a statistical software tool (www.jmp.com) with a good graphical user interface and an easy tool to carry out statistical data analysis. It can be used for building regression trees and finding interactions between various factors of a model. We used it for analysis of the data obtained from our simulations. Additionally, it was used for conducting regression analysis on factors defined in our DOE.

B. LITERATURE REVIEW

Previous studies on convoy protection and employment of unmanned systems like unmanned surface vehicles (USVs) were reviewed before framing of the problem and establishing the research questions. Although these previous studies do not cover the scope of this thesis, their approach towards the problem and methodology to evaluate the various convoy protection tactics were adopted to some extent.

Chapter 10 of U.S. Navy (1946) *Antisubmarine Warfare in World War II OEG Report No. 51* provides an analytical approach to convoying and escort of shipping. It provides an insight into how to approach the problem, but the work is limited to protection of convoys against submarine torpedo attack only. The authors used

mathematical formulas and real-world data of U-boats attacks on convoys in World War II to highlight that convoy protection is more effective by concentrating forces around the convoy (i.e., close escort operations in the form of sector/skeleton screen). They carried out sensitivity analysis on the size and speed of convoys and found that larger and faster convoys had low loss rates. This was an interesting observation and reinforced the importance of convoy protection under subsurface threat.

In his master's thesis, Opcin (2016) used SIMKIT (a JAVA-based discrete event simulation (DES)) to explore some of the factors in protecting a high value unit (HVU) against ASCMs fired from air or surface platforms. He developed three scenarios based on the number of Blue surface combatants (guided missile frigates - FFGs) protecting the convoy and the number of attacking Red platforms. The Blue FFGs were formed around the convoy in air defense mode. Ali's study concluded that weapons' specifications of the Red ASCMs and Blue force surface-to-air missiles (SAM), and the staying power of HVUs, are critical factors in determining the effectiveness of air defense in such operations. The study provides an insight into various factors to be considered for convoy protection, but it is limited to air threats only and a single HVU, not a full convoy.

In his master's thesis, Salim (2015) used MANA software to simulate the defense of a convoy under subsurface torpedo threat in littoral waters. He developed six scenarios over a battlefield of 140 × 40 NM in which he varied the type and number of Blue platforms escorting an HVU in a close escort operation. He used FFGs, ASW helicopters and unmanned surface vessels (USV) capable of lowering sonar to a certain depth. The USV was considered to be capable of detecting the enemy submarine but had no capability of engaging it. Upon detection, the USV passed the contact information to the force escorting the convoy, which dispatched an escort to prosecute the contact. Salim developed up to eight scenarios using various platforms like surface vessels, helicopters and USVs and established that unmanned systems can be of good value in antisubmarine operations. The USVs were considered to be inferior to the MDUSVs that this study analyzed. The MDUSV in this study was capable of carrying torpedoes to engage the enemy submarine in addition to detection. It also carried TALON, which is used for

detecting surface contacts up to a range of 150 NM. Salim’s efforts focused on one-dimensional threat (underwater torpedo attack) and limited the threat to one submarine.

In his master’s thesis, Aydin (2000) developed a disposition mission model (DMM) using SIMKIT and MODKIT for protection of convoy against land-based ASCM threat in littoral waters. He focused on optimizing the positioning of units around HVUs based on the threat axis. The study varied the number of missile launching sites as well as the number of Blue escorts protecting the convoy. He also varied the stationing positions of escorts around the HVUs with respect to the threat axis to see if it had any significant impact on the convoy operation. Aydin concluded that stationing the escorting units up-threat greatly improves the probability of protecting the convoy. The study limited its scope to a one-dimensional threat (land-based ASCMs) with perceived threat axis.

Although none of the studies reviewed, addressed protecting a convoy in a multiple-threat scenario, they provide a good insight into what factors need to be considered for carrying out effective convoy operations. They also highlight the importance of analytical methodology and simulation software in analyzing this kind of operation.

III. MODEL AND SCENARIO DEVELOPMENT

A. MODEL DEVELOPMENT CONCEPT

In this chapter, we provide a more detailed description of our analytical approach. The baseline scenario is based on sector screen around the convoy. Then we extend the model by introducing various tactics and different types of platforms. We also vary the enemy submarine's weapon employment priority (missile or torpedo) to see if we need different defensive tactics for different enemy attack plans. Additionally, we vary the Red submarine concealment to represent different acoustic environments and sonar performance. Our final aim is to find the most robust defensive solution, no matter what weapon priority the enemy submarine prefers and what the acoustic environment is.

A sector or skeleton screen is generally recommended for convoy operation against a subsurface threat, but necessary amendments are required for a particular type of tactical situation. We considered the sector screen in which units are assigned sectors around the convoy with specific sector width and depth. Each unit is to patrol its assigned sector and search for submarines with active or passive sonars per sonar policy implemented by the ASW commander. The amount of patrolling and size of the sector depend on the speed advantage of the escort ships over the convoy ships and the escort ships' tactical sonar ranges (TSRs). Based on the availability of units and perceived threat, ships may be deployed in layered defense within a sector screen. These layers are called inner screen, intermediate screen and outer screen, as shown in Figure 5.

1. Inner Screen

Inside the inner screen, units are stationed at a distance of 4–8 NM around the convoy. The inner screen is formed primarily against the submarine trying to gain a torpedo firing position on the convoy. This is the most preferred of the three screens and is the only option if available units are insufficient to form multi-layered screens.

2. Intermediate Screen

In the intermediate screen escorting units are stationed at a distance of 25–30 NM from the convoy. This provides a defense in depth against a submarine approaching for a torpedo attack and increases protection against submarines carrying medium-range missiles. It also helps detect any fast patrol boat (FPB) and neutralize it at further distance from the convoy than an inner screen is capable of doing.

3. Outer Screen

Outer screen escorting units are stationed at a distance of up to 100 NM from the convoy. This screen is put in place only if sufficient units are available to form the inner screen. It carries all the advantages of the intermediate screen but with some tradeoff between the defense against the torpedo and missile attack. We endeavored to explore this in our study.

Apart from the sector screen, we also analyzed the concept of the zone defense option, in which units are assigned static areas along the convoy's transit route. These units patrol their respective areas and establish safe zones for the convoy with no close escort. Although it has been established that this tactic underperforms the screen formation, we wanted to explore the introduction of MDUSVs into the scenario and particularly in the zone defense function. The MDUSVs are low-cost unmanned platforms that are specifically designed for detection, tracking and attacking submarines. Keeping in view that they have no self-defense against the ASCMs, however, we considered their deployment in conjunction with surface platforms. This is explained in detail later in this chapter.

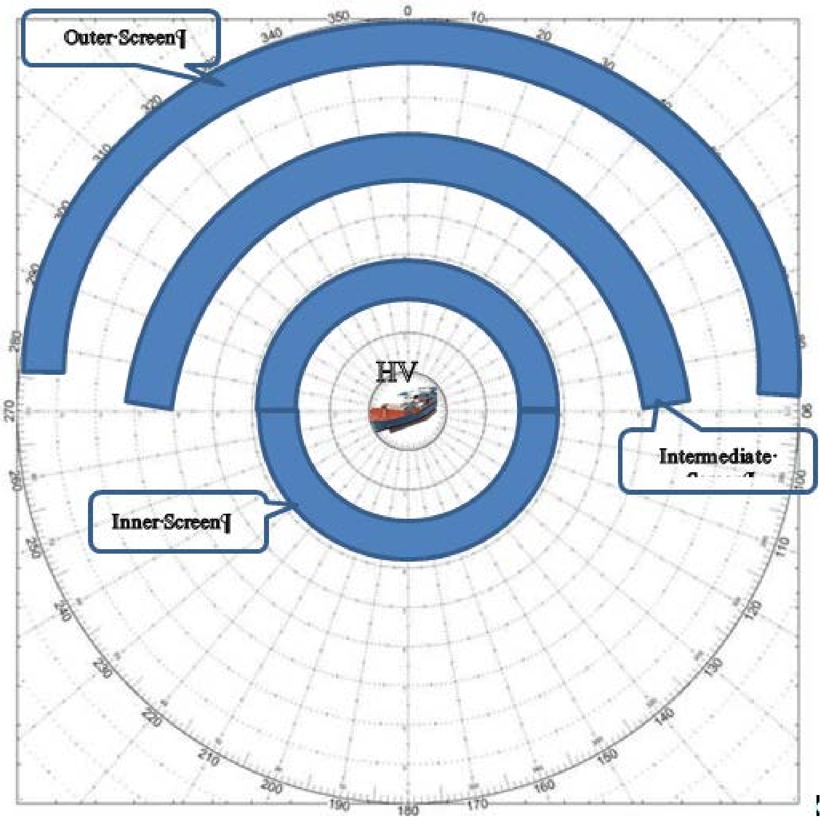


Figure 5. Convoy protection screen: Shown are screen layers in defense of the convoy's main body.

B. PROBLEM STATEMENT

In a full combat scenario, Blue force wants to transfer vital supplies such as ammunition and fuel from its main supply base to one of its forward stations. The whole area of operation (AOO) was considered to be 540 × 540 NM. We assumed that Blue has achieved air superiority over the whole AOO, as shown in Figure 1. Blue has established a coastal defense up to 50 NM against all types of threat (air, surface and subsurface). Blue maintains a continuous surface picture of up to 100 NM from the bases. Any type of surface threat in that range is investigated and neutralized by shore-based air assets. Based on these Blue force land-based capabilities, the convoy's transit threat is scoped down to mid-ocean enemy subsurface and surface platforms only. Red force may deploy up to three conventional attack submarines (SSKs) capable of launching long-range ASCM and three guided missile destroyers (DDGs) armed with ASCMs. Blue wants to

find the best tactics to accomplish the logistics task with the minimum number of casualties against the expected threat.

C. RED PREDICTED ENGAGEMENT MODEL

We assumed that Red force utilizes the best strategy to detect the convoy and deploys the three submarines and three DDGs, as shown in Figure 6. All Red platforms are conducting barrier search across the transit track of the convoy; submarines with a search speed of 4 knots and ships with a search speed of 12 knots. The area of operations is a 400 × 500 NM rectangle for submarines and a 300 × 500 NM rectangle for surface ships. The two types of Red platforms must operate separately to avoid engaging their own forces. The surface ships operate in formation while the submarines work independently. We assumed perfect information sharing between the surface ships, whereas there are no continuous communications between the submarines. For this tactical situation, the individual operating areas were defined as 100 × 100 NM for each submarine and 200 × 500 NM for the surface ship formation, as shown in Figure 6. The submarines' patrol position may be anywhere on the 100 NM length of their respective areas at the start of a run, each patrolling for 100 NM across the convoy transit track. The same is true for the surface ships operating in formation, but they search over an area of 200 × 500 NM.

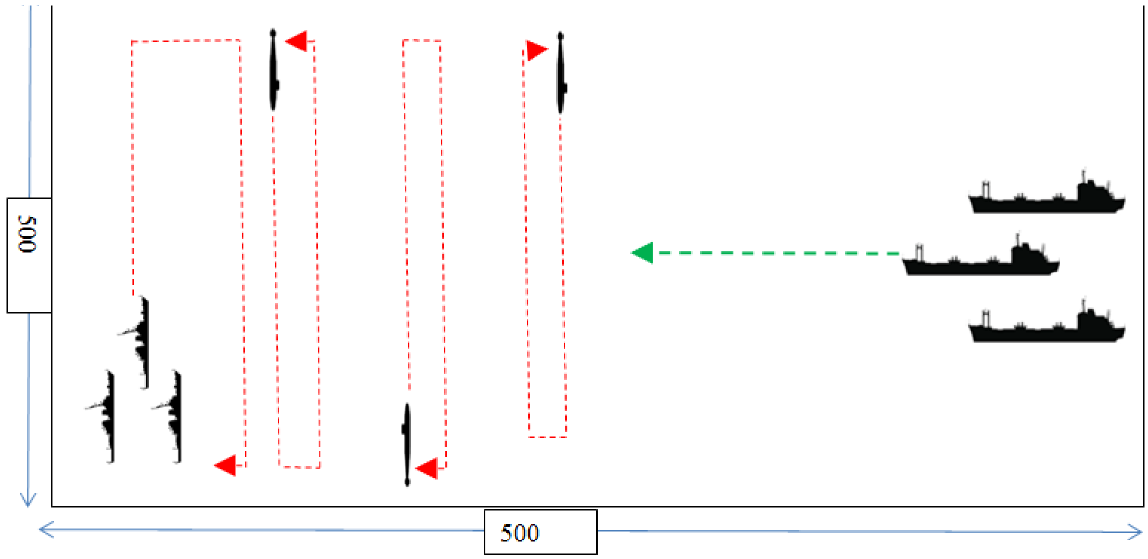


Figure 6. Red predicted engagement model: Red has established four layers of barrier search against the Blue convoy (three with submarines and one with surface ships).

D. CAPABILITIES AND TACTICS OF RED COMBATANTS

As mentioned before, the Red force is composed of two types of platforms: surface ships (DDGs) and submarines. Their capabilities and characteristics related to our model are described here to establish the bases for the different scenarios and analysis of the results.

1. Red Submarines

There are three Red submarines in our model. All are identical in their capabilities and reflect People’s Liberation Army (Navy) (PLAN) Type-93 SSNs. Their characteristics are as follows:

Max Speed

The submarine is capable of doing a maximum speed of 20 Knots, which it uses only when avoiding a torpedo or positioning herself for torpedo attack on the convoy. The submarine patrols its area of responsibility using a search speed of four Knots.

Torpedo

1. Range: The maximum range of the torpedo is 24 NM, but given that its single-shot kill probability is range dependent, the submarine will not fire its torpedo on any target unless within 13.5 NM (25000 m), at which it has at least 50% chance of hitting the target. Therefore, we limited the torpedo's maximum range to 13.5 NM (25 Km) in the simulation.

2. Capacity: The submarine's total weapon carrying capacity is 20, which can be any mix of missiles and torpedoes. We considered a mix of 12 torpedoes and 8 missiles.

3. Salvo size: The submarine's rate of fire is adjusted in a manner so as to allow it to fire a salvo size of two against a target. If the target is killed, it stops firing; otherwise, it carries out another salvo on the same target.

4. Single shot kill probability (SSKP): The torpedo is considered to be active guided and needs to search, detect, track and hit the target once fired by the submarine. Therefore, the probability of killing a target given that it is detected with a single shot is range dependent. SSKP of the torpedo is calculated against the ranges using Gaussian distribution and shown in the Table 1.

Table 1. Range dependent SSKP of Red submarine's torpedo.

Range (m)	2000	6000	12000	18000	25000	35000	45000
SSKP	0.9	0.8	0.6	0.55	0.5	0.3	0.1

Anti-Ship Cruise Missile (ASCM)

1. Range: The maximum range of ASCM is 136 NM, but the missile firing is tied to detection of the Blue convoy and/or surface combatants by its radar. Since the radar detection range of a submarine is in the order of 30–40 NM, the firing range of its missile is limited to 40 NM only. In our simulation, we used 40 NM as its maximum range.

2. Capacity: As mentioned earlier, the submarine is capable of carrying 20 weapons, eight of which are considered to be ASCMs.

3. Salvo size: The submarine is considered to use ASCMs against the convoy only. It will attack with all the available ASCMs in a single eight-missile salvo. We adjusted their rate of fire such that their firing spanned two minutes, however.

4. Accuracy and single-shot kill probability (SSKP): The missile's probability of hit against a convoy ship is considered to be 0.9 at all ranges

for almost all the ASCMs. MANA does not provide an option to define different staying power of a single agent for different incoming weapons, however. This means that although a cargo ship has a higher likelihood of surviving a missile hit than a torpedo hit, we could not reflect that in the simulations. As a result, we limited the missile probability of hit to 0.7 in order to incorporate that the effect of a missile is less than a torpedo.

Sonar

Per tactical procedures, submarines use passive sonar search policy when searching for a target. Since the convoy generates a high level of radiated noise, it becomes easier for the submarine to detect and classify at longer ranges. Keeping these factors in mind, we set the submarine's sonar characteristics as follows:

1. Maximum range of detection: 40 NM.
2. Range dependent probability of detection/classification: Per tactical procedures, a contact detected by submarine is further investigated for classification as an enemy, friendly or foe. This classification is aggregated for our simulation and the probability of detecting and classifying a target at different ranges is shown in Table 2.

Table 2. Range dependent probability of detection of Red submarine's sonar.

Range (m)	2000	6000	10000	15000	20000	25000	31000
Classification and Detection Probability	0.9	0.84	0.76	0.65	0.5	0.3	0.1

Radar

1. Maximum range: 40 NM.
2. Probability of detection and classification: The radar's probabilities of detection and contact classification are range dependent and are shown in Table 3.

Table 3. Range dependent probability of detection of Red submarine's radar.

Range (NM)	10	15	20	30	40
Classification and Detection Probability	0.9	0.8	0.7	0.6	0.5

2. Submarine Tactics

The submarine employs one of two attack courses of action based on its priority of weapon firing. These are to close the convoy to conduct a torpedo attack and then open the range and launch a missile salvo, or vice versa. The two options are explained in the ensuing paragraphs.

(1) Submarine Attacking with Torpedo First Then Missile (Tactic 1)

In this option, the submarine endeavors to gain a torpedo firing position within the limiting line of approach (LLA). Upon gaining contact, the submarine shapes its course to be within 30 degrees off the MLA by the time or before the convoy is within 5 NM (Figure 7). Upon gaining the intended position, it stops and starts waiting for the Convoy to be within torpedo firing range (13.5 NM in this study). Provided the submarine escapes detection and neutralization by the escorts during its approach, it fires all of its torpedoes on the Convoy when in range. If the submarine is detected and engaged by the escorts, it abandons its attack. If the submarine escapes attack from the escorts, it prepares to carry out a missile attack as per criteria described in the next section.

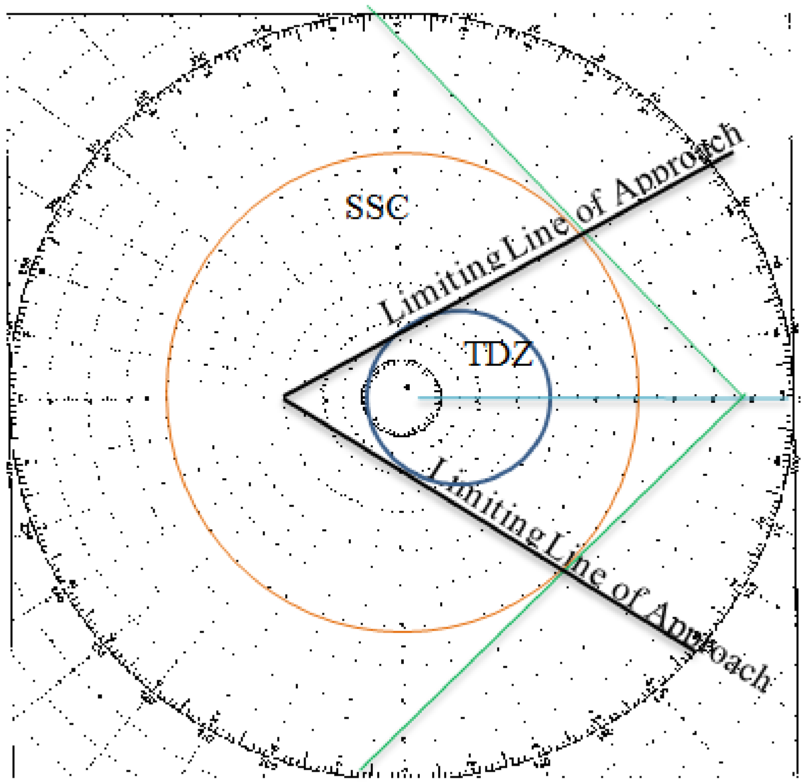


Figure 7. Submarine limiting lines of submerged approach: This figure shows the arcs in which the submarine must be to position for a torpedo attack. The torpedo danger zone (TDZ) circle bounds the area which the submarine may attack from.

After the torpedo attempt, the submarine will wait for the convoy to open up to a distance of 20 NM. Then, the submarine uses radar to gain targeting data and fire all ASCMs on the convoy. After the first missile launch, the submarine's radar remains active throughout the combat. The missile launched has 0.8 probability of hit, but due to escorts being in close vicinity of the convoy ships in the close escort model, it can home on to either with a probability of 0.5 given that it hits. The escorts then use an anti-air weapon (surface-to-air missile) to defend against the incoming missiles. In the zone defense model, they are engaged if the missile is detected by the Blue surface combatants and is within the range of their surface-to-air missile missiles. During this "torpedo first, then missile attack" tactic, a submarine remains covert and silent until it conducts the torpedo attack, which challenges the surface escorts in detecting the submarine. The

escorts' chances of detecting and killing the submarine if a close escort tactic is selected is higher than if in a zone defense, however.

(2) Submarine Attacking with Missiles First Then Torpedo (Tactic 2)

In this case, the submarine engages the convoy with missiles upon classification of the convoy, hoping to kill the maximum number of cargo vessels or weakening the convoy protection by destroying escorts. The submarine then positions itself for torpedo attack on a weakened convoy and escort group. In this tactic, however, the submarine launching missiles exposes its position to the Blue surface combatant force, which establishes a datum and detaches two surface ships as a search and attack unit (SAU). The SAU's presence restricts the submarine from an unimpeded torpedo attack on the convoy after carrying out the missile attack. We will compare the two tactics in the analysis section to find out the best option for the Red submarines.

The Red submarine tactic options apply to all the scenarios mentioned in this document to determine the most robust Blue defensive model regardless of submarine attack tactic.

3. Red Surface Ships

We considered three identical Red surface ships (DDGs) in our model. Their capabilities reflect China's Luyang class destroyers and are as follows.

(1) Maximum Speed

The surface ships are capable of 30 knots speed, which they use when they have detected the convoy and want to close it to fire missiles. They also use 30 knots of speed when they are out of ASCMs and want to get out of Blue ASCM range. In the absence of any contact with the convoy, however, they patrol their area at 12 knots in barrier search pattern.

(2) Torpedo

Each DDG carries six torpedoes, which they use against Blue submarines if deployed in the AOO as in the zone defense model. They also use torpedoes against Blue

convoy ships if they are not accompanied by close escorts and the convoy ships survive their missile attack. The characteristics of the torpedoes are as follows.

1. Max range: 7.6 NM (14 Km).
2. Capacity: Six
3. Salvo size: Two
4. Single shot kill probability (SSKP). SSKP of the torpedo is range dependent and is shown in Table 4.

Table 4. Range dependent SSKP of Red DDG's torpedo.

Range(m)	500	4000	8000	12000	14000
SSKP	0.9	0.8	0.6	0.5	0.3

(3) Anti-Ship Cruise Missile

1. Maximum range: The missile's maximum range is 136 NM but its firing is tied to detection and classification of the Blue convoy and its escorts. Since the radar ranges of the Red surface ships are in the order of 60–70 NM, their engagement range is limited to 70 NM.
2. Capacity: 18.
3. Salvo size: The salvo size is two against Blue surface combatants and 18 against all the convoy ships.
4. Probability of hit and kill: The probability of hit and kill is aggregated to 0.7 at all ranges. This aggregates the probability of hit (.9) with the probability of kill given a hit (.8).

(4) Active Sonar

The Red surface ships carry active sonars, which are used for detection of Blue submarines (present in zone defense model only) and are activated only if they are attacked by a torpedo or they are in contact with the Blue force. The sonar's maximum range is considered to be 16.7 NM (31 Km), but its probability of detection is range dependent and shown in Table 5.

Table 5. Range dependent detection probabilities of Red DDG's sonar.

Range(m)	2000	6000	10000	15000	20000	25000	31000
Classification/ Detection Probability	0.9	0.8	0.7	0.65	0.5	0.3	0.1

(5) Radar

1. Maximum range: 60 NM.

2. Probability of detection and classification: Detection and classification of the radar is range dependent and shown in the Table 6.

Table 6. Range dependent detection probability of Red DDG's radar.

Range (NM)	5	15	30	45	60
Detection and Classification Probability	0.9	0.85	0.75	0.5	0.2

E. BLUE DEFENSE OPTIONS

Blue has basically two escort station defense options: close escort and zone defense. These are extended into 38 sub-models and are explained in the remainder of this chapter.

1. Close Escort Operation

The close escort operation tactic provides a protective shield to the convoy by deploying surface and/or organic platforms in close vicinity around the convoy. It is basically meant for protection against the Red submarine trying to penetrate the screen for carrying out torpedo attack and defends the convoy against incoming Red ASCMs. Using a close escort tactic, however, means the escorts minimize the chance to kill the submarine before it attacks with missiles if that is Red's preferred tactic. They must then defend against the entire missile salvo. If the number of escorts available allows multiple screens at different ranges from the convoy in a layered defense, this may be mitigated

somewhat. Based on this concept, 28 scenarios were developed and are explained later in this chapter.

2. Zone Defense

This model makes the transit area a "green zone" for the convoy by denying the operational area to adversary's ships and submarines through deployment of forces along the convoy's transit track. Each unit is assigned a static geographical area that is patrolled rigorously to avoid any ingress of enemy force into the convoy transit area. No escorts are assigned directly to the convoy. As such, the zone defense leaves the convoy unprotected against close-in attack. Another risk with the zone defense is that searching a large area for a Red submarine is a highly challenging task.

F. BLUE ASSETS AND THEIR CAPABILITIES

Blue has seven DDGs, three SSNs, two antisubmarine warfare (ASW) helicopters, two Tactically Exploited Reconnaissance Node (TERN) unmanned air platforms and two Medium Displacement Unmanned Surface Vessels (MDUSV). The close escort model uses only DDGs and/or helicopters, whereas the Blue SSNs can be deployed in zone defense model only. The total number of DDGs, SSNs and/or helicopters is limited to nine platforms in the basic models (without unmanned systems). Additionally, up to two TERNs and six MDUSVs may be deployed in each model. Capabilities of Blue assets are as follows.

1. Surface Ship Capabilities

Blue surface ship escort capabilities are defined in such a manner so as to reflect Arleigh Burke class destroyers. Due to software limitations and some tactical considerations, however, several characteristics are amended to best fit the model and reflect real world effects. These are mentioned below.

(1) Blue Ship Torpedo

1. Range: Maximum range of the torpedo is considered to be 10.8 NM (20 km), reflecting Mk-46 torpedo.

2. Capacity: Total capacity is considered to be six with no reloading during an engagement.

3. Salvo size: Torpedo salvo size is limited to two.

4. Single shot probability of kill (SSKP): The Mk-46 torpedo is an active-guided torpedo. Therefore, it has to search, acquire and track the target prior to attacking it. All these factors have been aggregated into its SSKP, which is range dependent and shown in Table 7.

Table 7. Range dependent SSKP of Blue DDG's torpedo.

Range	2000	5000	10000	15000	20000
SSKP	0.9	0.8	0.7	0.6	0.5

(2) Anti-Air Weapon

The anti-air weapon reflects a U.S. Navy Standard Missile 6 (SM-6), which is used for destroying the incoming Red ASCM. Its capabilities used in the model are as follows.

1. Range: Maximum range of SM-6 is 172 NM. Its firing on a target, however, is tied to acquiring it on ship-borne fire control radar, which is limited to 60 NM (max). Therefore, its effective range in the model is limited to 60 NM. We varied this range in the experiment between 15 and 60 for sensitivity analysis.

2. Capacity: Total capacity is 100. We varied this factor between 10 and 100 for sensitivity analysis, however.

3. Salvo size: The salvo size is two against a single inbound Red ASCM.

4. Single shot probability of kill (SSKP): We considered the missile to be active guided. Therefore, it had to search, detect and track the target prior to kill. To incorporate these factors, we estimated its SSKP to be 0.7.

Air Search and Fire Control (FC) Radar

Air search and fire control radar performance are combined and limited to 70 NM. Also, since the Red ASCM is considered to be a sea skimming missile, it cannot be detected at a range greater than 60 NM. Additionally, the Red surface ships will launch ASCMs at a range of around 60–70 NM and the submarine at around 30–40 NM. This transmission is considered to be picked by the escort's electronic support measure (ESM)

systems, which go active on air search and surface search radars. Detection of the incoming missile by the air search radar and a target lock by the fire control radar are aggregated in Table 8.

Table 8. Range dependent detection probability of Blue DDG's radar.

Range (NM)	5	15	30	50	70
Detection/ Classification Probability	0.9	0.85	0.75	0.5	0.2

(3) Sonar

The Blue escort ship's sonar is considered to be the SQS-53C in active mode and used primarily for detection and classification of Red submarines. Its maximum range is considered to be 16.7 NM (31 Km), and its probability of detection and classification are aggregated in Table 9.

Table 9. Range dependent detection probability of Blue DDG's sonar.

Range (m)	2000	6000	10000	15000	20000	25000	31000
Detection and Class Probability	0.9	0.84	0.76	0.65	0.5	0.3	0.1

(4) Surface Search Radar

1. Maximum range: 70 NM.
2. Probability of detection and classification: These are range dependent and are shown in Table 10.

Table 10. Range dependent detection probability of Blue surface radar.

Range (NM)	10	20	35	50	70
Detection and Class Probability	0.95	0.9	0.85	0.7	0.5

2. Nuclear Submarine (SSN) Capabilities

Blue SSNs are considered to be Los Angeles class submarines in the model. In the simulation, they will attack Red forces with torpedoes only. Their characteristics are listed below.

(1) Sonar

1. Max range: 27 NM (50 km).
2. Probability of detection and classification: The Blue submarine must search for Red submarines and Red surface ships. Its detection probabilities are range dependent and shown in Table 11. It must be noted that these probabilities are effective against the Red surface ships. Against Red submarines, they are decreased by 40–50% since the submarine is 40–50% quieter than ships.

Table 11. Range dependent detection probabilities of Blue SSN's sonar.

Range (m)	2000	6000	10000	15000	20000	30000	40000	50000
Detection and Class Probability	0.9	0.84	0.76	0.65	0.5	0.4	0.25	0.1

(2) Torpedo

1. Maximum range: Maximum range of the torpedo is considered to be 24 NM, but the submarine is expected to fire it only when it can hit the target with a probability greater than or equal to 0.5. In order to incorporate this decision factor into the simulation, we limited its maximum range to 13.5 NM (25 Km).
2. Capacity: 14 torpedoes with no reloading
3. Salvo size: Two.
4. Single shot kill probability (SSKP): The SSKP of torpedo is range dependent based on the torpedo speed and active guidance. Its SSKP versus range is shown in Table 12.

Table 12. Range dependent SSKP of Blue SSN's torpedo.

Range (m)	2000	8000	12000	16000	20000
SSKP	0.9	0.8	0.7	0.6	0.5

3. Helicopters

Helicopters are used in close escort model only and deployed in the intermediate or outer screens. The helicopters use dipping sonar to search and torpedoes to attack Red submarines. When deployed, they follow Air-plan 42 as shown in Figure 8. The search speed of the helicopters in outer or intermediate screen is 21 knots. The helicopter dips its sonar for 10 minutes at 7 NM spacing at 90 degrees to the previous line of advance (LOA). Its capabilities are mentioned in the ensuing paragraphs.

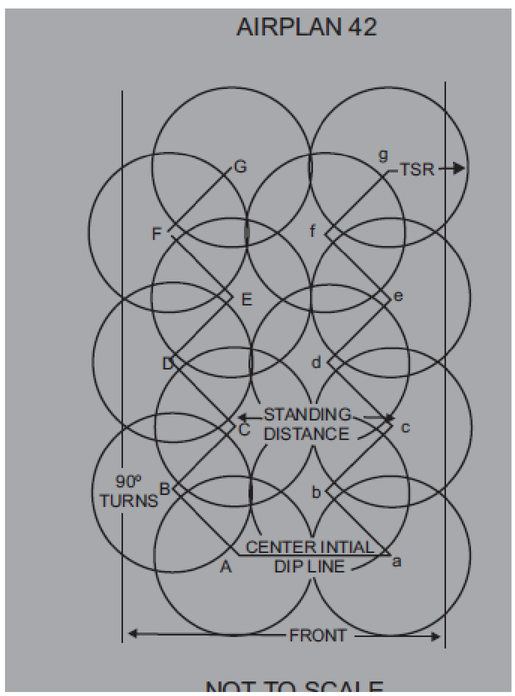


Figure 8. Helicopter search plan: Results in a zig-zag search pattern along the convoy's intended track.

(1) Fuel

The helicopter carries fuel sufficient enough to undertake the mission continuously for 3 hours in addition to its two-way transit time to its screen position. The refuel time is dependent on its distance from the parent unit and is expected to take around 2 hours and 45 minutes as calculated using its speed and deployment distance.

(2) Dipping Sonar

1. Max range: 5 NM (9.26 Km).

2. Probability of detection and classification: This factor is range dependent and shown in Table 13.

Table 13. Range dependent detection probability of Blue helicopter's sonar.

Range (m)	2000	4000	6000	8000	9260
Detection and Class Probability	0.9	0.82	0.72	0.65	0.5

(3) Torpedo

1. Maximum range: 9.72 NM (18 Km).

2. Capacity: The helicopter carries two torpedoes with the option of reload. The reload time is dependent on the range of the helicopter from the parent unit and is set to be 2 hours and 45 minutes as calculated using its speed of 200 Knots.

3. Salvo size: The helicopter launches two torpedoes against the Red submarine. Considering the factor that it will be using both of its torpedoes at a time, we merged the two torpedoes and calculated the combined hit and kill probabilities.

4. Probability of kill: As the two torpedoes are merged to one, so the probabilities shown in Table 14 are the combined kill probabilities of the two torpedoes carried by the helicopters.

Table 14. Combined probability of kill of helicopter's torpedoes.

Range (m)	2000	5000	10000	15000	18000
Accuracy	0.9	0.85	0.75	0.51	0.19

4. Tactically Exploited Reconnaissance Node

The Tactically Exploited Reconnaissance Node (TERN) (Figure 9) is an unmanned airborne platform (drone) with tail-sitting capability designed and developed by the U.S. Defense Advanced Research Projects Agency (DARPA). It is a medium-altitude long-endurance (MALE) persistent (long dwell time) ISR platform launched and recovered from smaller combatants and expects its test flight in 2018 (Wesserbly 2016). It takes off and lands using its own power with the help of a pneumatic launcher and recovery system. A similar system is used by smaller UAVs like Insitu RQ-21 Blackjack.1, etc. It augments reconnaissance capability and striking distance of surface combatants, thereby increasing their available reaction time and offensive range. Its combat capabilities are mentioned below.

Figure 9. Tactically Exploited Reconnaissance Node (TERN) (Source: http://www.darpa.mil/news-events/2015-12-28).

General Characteristics

1. Endurance: It is a long-endurance platform that can cover an area of 600–900 NM based upon the payload. Its endurance is set to be 3 hours with a speed of 200 Knots.

2. It is capable of multi-spectral sensing overland and overwater for Information Surveillance and Reconnaissance (ISR) purposes.

3. Weapons: It can carry a payload of 1000 lbs. Payload may be a Griffen missile, Laser-guided bomb (LGB) or lightweight torpedo based upon its mission requirements and role. In our study, we used it in IR mode and, therefore, it was unarmed.

4. Radar: It can carry a radar system that can cover a range of 170 NM. We used the radar in infrared (IR mode) only for detection of Red surface combatants. Its probability of detection and classification are unclassified estimates and are in Table 15 below.

Table 15. Probabilities of detection and classification.

Range (NM)	10	20	35	50	70	80
Detection/ Class Prob	0.95	0.9	0.85	0.7	0.5	0.2

5. Medium Displacement Unmanned Surface Vessel

The ACTUV, now Medium Displacement Unmanned Surface Vehicle (MDUSV, Figure 10), is a self-deployed surface unmanned system capable of on-station times of 60–90 days with ranges of 900–10,000 nautical miles depending on speed (3–24 knots) and payload (5–20 tons). In its ASW role, it receives off-board cueing and hand off, then conducts an overt trail with active sonar. It can act as an ASW scout in coordination with area ASW assets like the P-8, conducting large acoustic surveillance using passive and/or active bistatic Surveillance Towed Array Sensor System (SURTASS). It can deploy three Mk-54 or six CRAW torpedoes. In its ISR role, it can work with a surface adaptive force package as an advanced scout employing passive RF, IO/IR and UAV sensors, and in an offensive role, can carry eight RBS-15 surface-to-surface missiles.

Figure 10. MDUSV with TALON. Image from DARPA at http://www.darpa.mil/news-events/2016-10-24.

In this study, we used the MDUSV in ASW role with three Mk-54 torpedoes and sonar capability. The torpedo characteristics are the same as for Blue surface combatants.

G. SCENARIOS DEVELOPMENT

Scenarios developed in this study were based upon the two basic defense options: close escort operation and zone defense. These were then extended to 36 different tactical scenarios based upon escort’s positions, type of platform and Red and Blue force tactics, which are discussed in the ensuing paragraphs.

Scenarios 1–14 uses Red submarine Tactic-1, in which the Red submarine attacks the convoy first with torpedo followed by missiles. We restricted the Red submarine from attacking the convoy with any missile until and unless it starts opening after initial detection and gets out of sonar detection range. If this happens, the Red submarine agent switches its radar ON and carries out a missile attack on the convoy. In case it is able to get in contact with the convoy and closes to torpedo firing range, it attacks the convoy with torpedo and endeavors to evade Blue counter attack. If it survives, it opens out and launches missile attack.

1. Scenario 1

This is the baseline scenario that provides a benchmark for our study. Seven surface combatants (DDGs) are stationed in the inner screen around the convoy. Each DDG is assigned a particular sector with specific width and size based upon their submarine search rate and tactical sonar ranges (TSR). The sectors are shown in Figure 11 and described in Table 16.

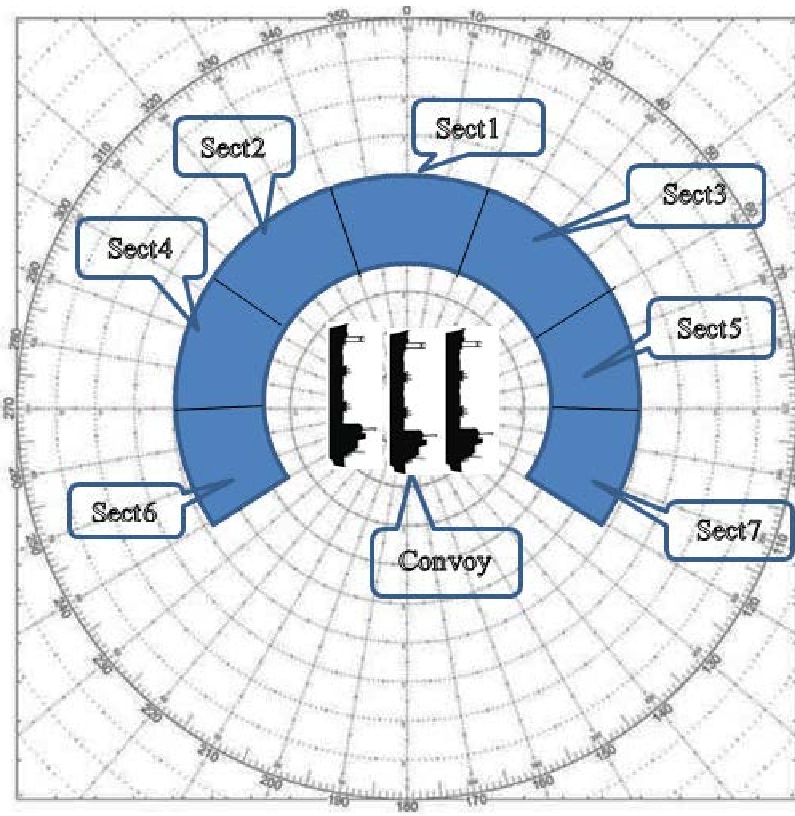


Figure 11. Model Scenario 1 representing the relative sector positions.

Table 16. Description of sectors — Scenario 1.

Sector	Width	Depth	Remarks
1	340–020	4–8 NM	Ships maneuver randomly in their sectors with speed of 21 Knots
2	300–340	-’’-	
3	020–060	-’’-	
4	270–300	-’’-	
5	060–090	-’’-	
6	240–270	-’’-	
7	090–120	-’’-	

Convoy speed of advance (SoA) is 17 Knots. The escorts are patrolling their sector in random manner at 21 knots. Maximum speed of escorts is 28 knots, which they use only when they are detached to engage a contact or when trying to put themselves between the convoy and the incoming detected threat. We assume that sonar policy is active for the escorts while passive for the Red submarines. Radar policy is silent until and unless the ESM picks up some threat radar signal from the adversary. We can assume that this happens just before the Red platform launches a missile.

2. Scenario 2

In this scenario, we introduced an outer screen. Again, the total escorts are seven DDGs; five of which are placed in the inner screen and two in the outer screen. The scenario setup is shown in Figure 12 and sectors are described in Table 17.

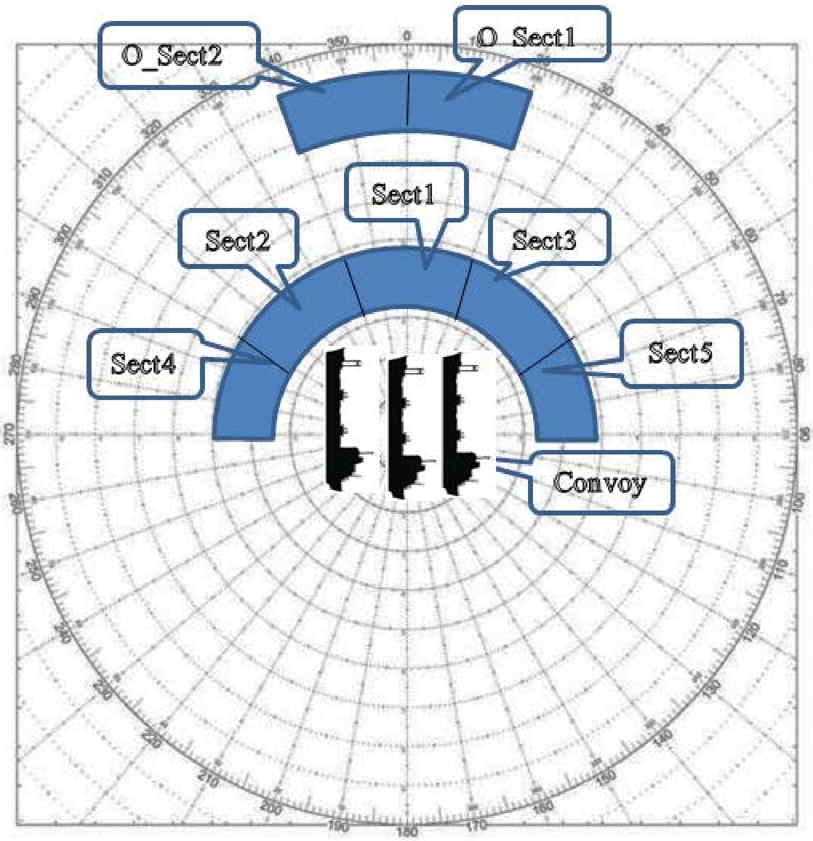


Figure 12. Model Scenario 2 representing the relative sector positions.

Table 17. Description of sectors — Scenario 2.

Sector	Width	Depth	Remarks
1	340–020	4–6 NM	Inner screen DDGs
2	300–340	-’’-	
3	020–060	-’’-	
4	270–300		
5	060–090	-’’-	
6	335–360	60–65 NM	Outer screen DDGs
7	000–025	-’’-	

All the escorts are capable of anti-air and anti-submarine operations and are carrying all the weapons and sensors as mentioned earlier. Red submarine avoids engaging the escorts in the outer screen until and unless attacked by the escorts, in which case it uses torpedoes only.

3. Scenario 3

It is the same as scenario 2, except that the outer escorts are now placed in the intermediate screen. The intermediate screen is formed at distance of 30 NM from the convoy and shown in Figure 13. The sectors are described in Table 18.

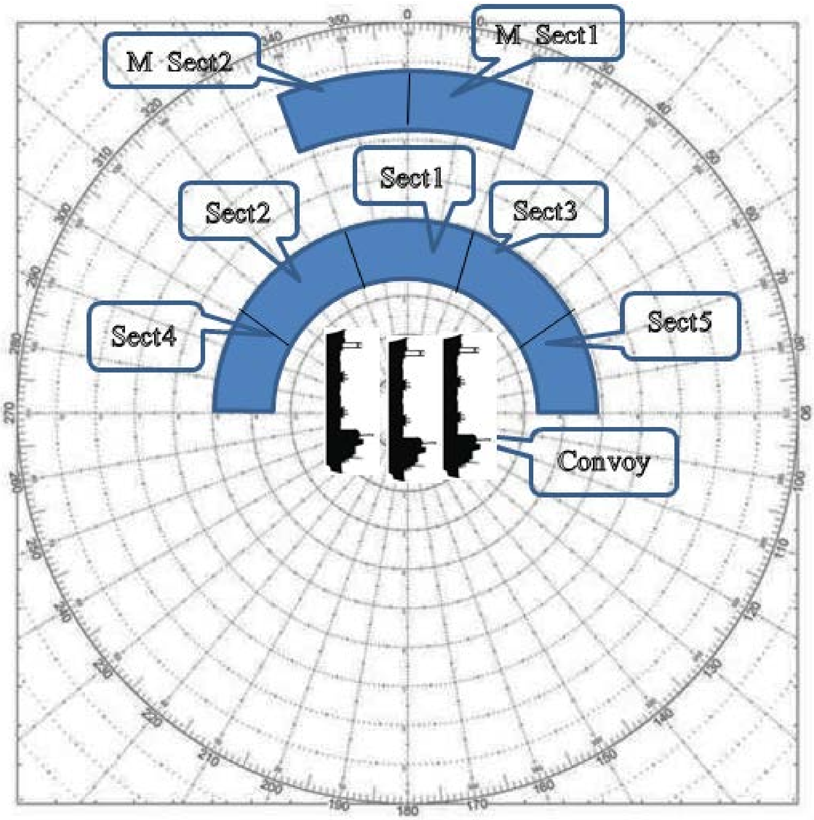


Figure 13. Model Scenario 3 representing the relative sector positions.

Table 18. Description of sectors — Scenario 3.

Sector	Width	Depth	Remarks
1	340–020	4–6 NM	Inner screen DDGs
2	300–340	-’’-	
3	020–060	-’’-	
4	270–300	-’’-	
5	060–090	-’’-	
6	335–360	30–35 NM	Intermediate screen DDGs
7	000–025	-’’-	

4. Scenarios 4 and 5

They are similar to scenarios 2 and 3, respectively, except that the outer and intermediate screen surface ships are replaced by helicopters. Helicopters are considered to have a concealment factor of 100% against enemy submarines as they cannot be attacked by a submarine. They follow air plan 42 as shown in Figure 7 with a speed of advance (SoA) of 17 Knots (same as of convoy). If a helicopter detects a submarine, it tracks, moves to torpedo firing range and attacks the submarine with both the torpedoes. If unsuccessful, it returns to its ship, reloads the torpedoes and returns to its previous position to follow the submarine until it kills it. There is a chance, however, that on return it loses the submarine, in which case it continues its search as planned.

5. Scenarios 6 and 7

They are similar to scenarios 2 and 3, respectively, except that there are two MDUSVs in the outer and intermediate screen in addition to the surface ships. MDUSVs are placed between the two outer and intermediate screen DDGs, providing protection against the ASCMs. They are equipped with TALON for surface surveillance up to 150 NM. As they are operating in close vicinity of the two surface ships, their TALON radar picture is available to the surface ships. Upon receiving any radar information on Red surface ships, the two Blue DDGs are dispatched to engage the surface contacts and rejoin upon mission success. The MDUSV’s subsurface picture is also shared with the surface ships and any contact is engaged jointly by the two MDUSVs and the two DDGs. The outer and intermediate screen sectors are redefined in Table 19 and shown in Figure 14.

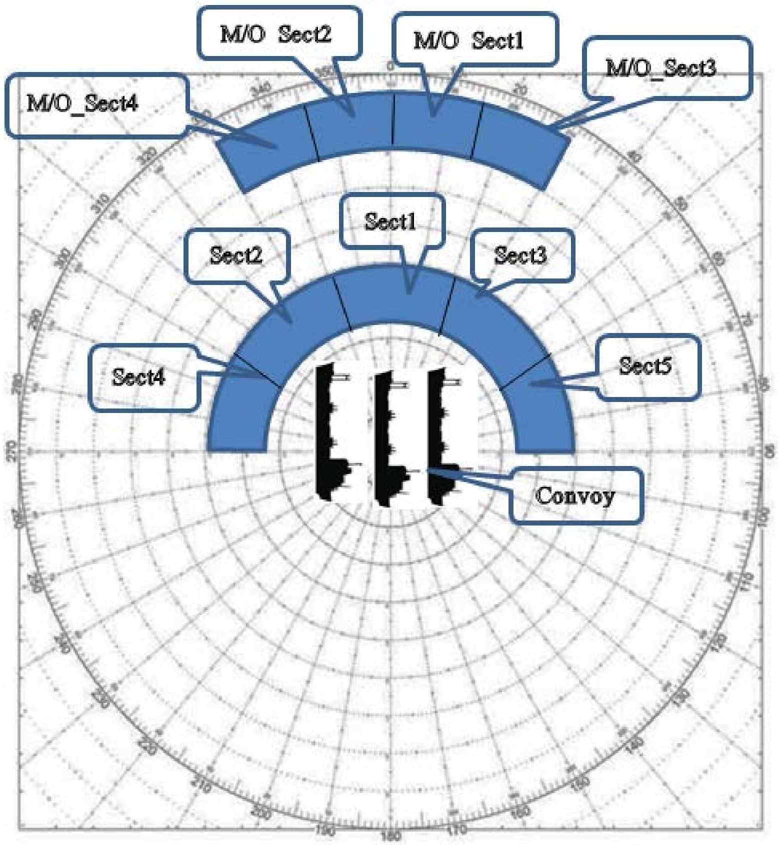


Figure 14. Model Scenario 3 representing the relative sector positions.

Table 19. Description of sectors — Scenario 6/7.

<table>
<tr><td>Sector</td><td>Width</td><td>Depth</td><td>Remarks</td></tr>
<tr><td>1</td><td>340–020</td><td>4–6 NM</td><td rowspan="5">Inner screen DDGs</td></tr>
<tr><td>2</td><td>300–340</td><td>-’’-</td></tr>
<tr><td>3</td><td>020–060</td><td>-’’-</td></tr>
<tr><td>4</td><td>270–300</td><td>-’’-</td></tr>
<tr><td>5</td><td>060–090</td><td>-’’-</td></tr>
<tr><td>6</td><td>345–360</td><td>30–35 NM or 60–65 NM</td><td rowspan="2">Intermediate/outer screen MDUSVs</td></tr>
<tr><td>7</td><td>000–015</td><td>-’’-</td></tr>
<tr><td>8</td><td>325–345</td><td>-”-</td><td rowspan="2">Intermediate/outer screen DDGs</td></tr>
<tr><td>9</td><td>015–035</td><td>-’’-</td></tr>
</table>

6. Scenarios 8–14

These scenarios are similar to scenarios 1–7 except that the models now have additional support of two TERNs searching in IR mode for Red surface ships. Upon identification, TERN passes the contact information to the force, which detaches two escorts with full dispatch to engage the targets and rejoin the formation on success. The TERN is recovered onboard upon completion of its search mission. Each TERN is allocated an area of responsibility of 400 × 250 NM to search half of the area of operations. The search is carried out in barrier search pattern parallel to the convoy track, with lateral track spacing of 50 NM, as shown in Figure 15.

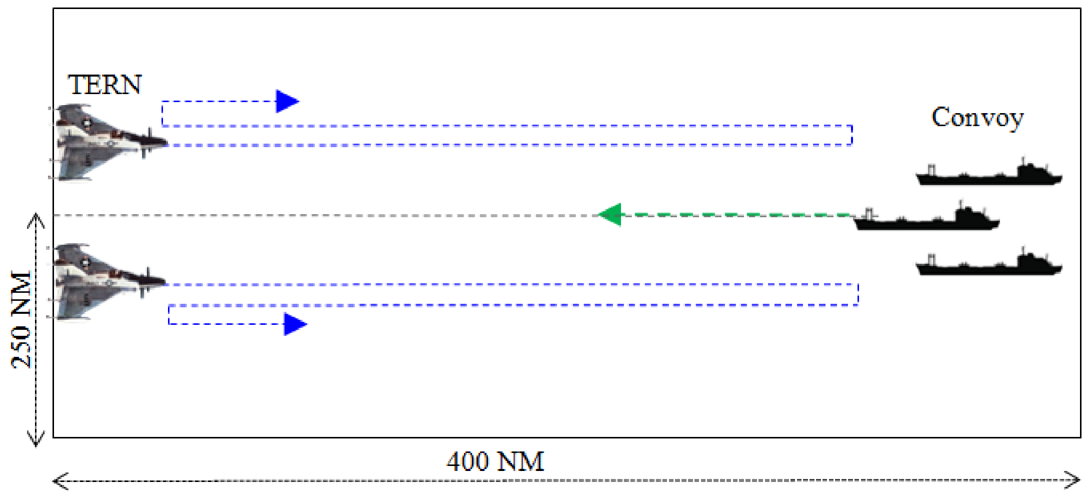


Figure 15. TERN employment — Scenarios 8–14: The TERN uses a ladder search fly profile parallel to the convoy's intended transit track.

7. Scenarios 15–28

These are similar to scenarios 1–14 except that the Red submarine prefers to attack with missile first, then close for torpedo attack. This is termed as Sub-tactic 2 in the model. It will be compared to Sub-tactic 1 (attack with torpedoes first) to see which has greater mission success for the submarine and the greater risk to Blue forces. The analysis will also provide insight into the robustness of various Blue defensive options against the different submarine attacking strategies.

H. ZONE DEFENSE MODEL

Zone defense model is based on the concept of making the whole area of transit a green zone (safe zone) for the convoy. This is achieved through employment of Blue assets across the AOO. Each unit is allocated a static area of responsibility that it protects against any intrusion by Red forces. Based upon the type of Blue platforms and Red tactics of weapon employment, the zone defense model has been extended to eight scenarios, which are explained below.

1. Scenario 29 (Red Submarine Tactic-1)

The basic zone defense model comprises six DDGs and three SSNs. They are deployed as shown in Figure 16. The whole area is divided into three main areas that are further divided into three sub-areas, one for each Blue platform. Central sub-areas are allocated to Blue SSNs and outer sub-areas to Blue DDGs. Each SSN has an area of responsibility (AOR) of 133 × 50 NM, whereas each DDG is patrolling 133 × 200 NM.

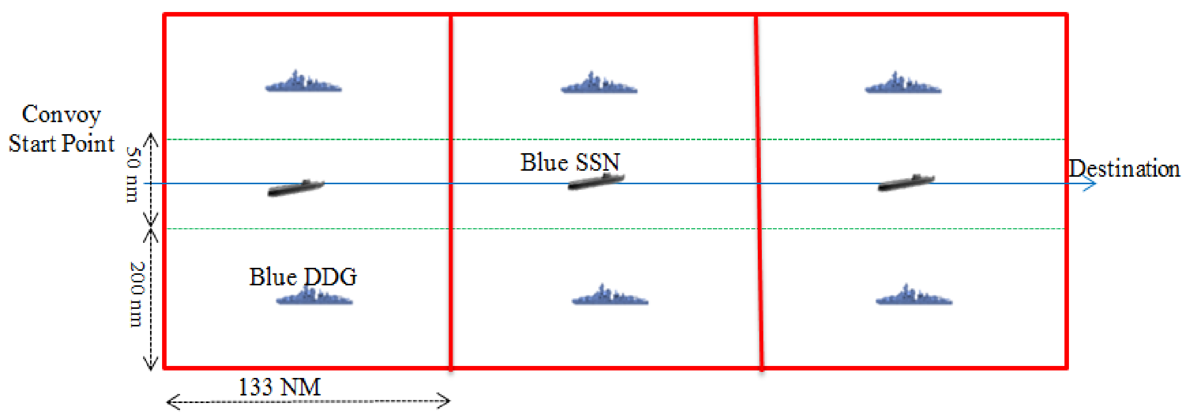


Figure 16. Blue zone defense model — Scenario 29.

The Blue assets are patrolling their respective areas in barrier search pattern parallel to the track of convoy as shown in Figure 17. This patrol pattern aims at blocking any intruder getting close to the track of convoy transit. DDGs in the main areas operate in support of each other but the submarine always operates independently. If a DDG detects a contact, it shares the information with all the Blue DDGs, but only the adjacent

DDG joins it in engaging the target. The Blue submarines are deployed to search and hunt the Red submarine and surface ships when passing through their AoRs.

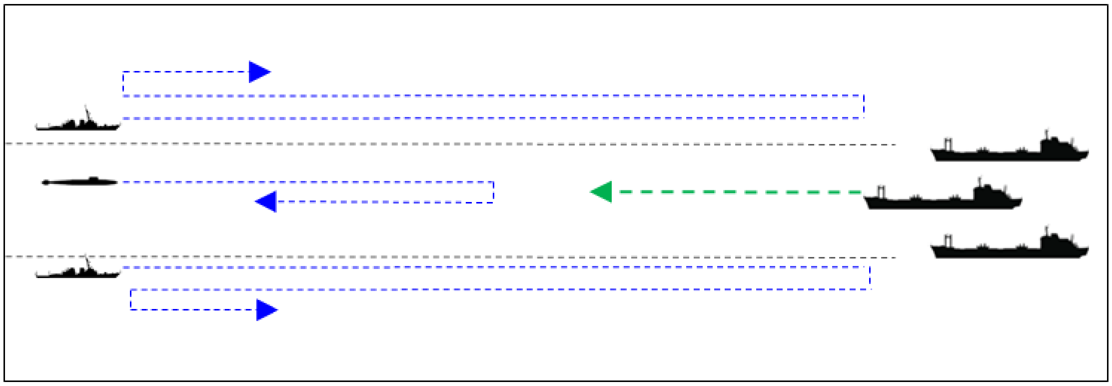


Figure 17. Blue zone defense model — search pattern: Blue ships and submarines search in a ladder pattern parallel to the convoy's intended track.

2. Scenario 30

Scenario 30 is similar to scenario 29 except that now it has the support of two TERNs operating in the same role as in close escort model. Their concept of operation is the same as mentioned in the close escort model.

3. Scenario 31

Scenario 31 is similar to scenario 29 except that the Blue SSNs are now replaced by the six MDUSVs. The MDUSVs are operating with TALONs, using their radar to increase the Blue surface surveillance range up to 150 NM. Their surface and subsurface picture is available to the Blue DDGs. The DDGs and MDUSVs in a main area respond jointly to any subsurface contact, whereas the Red surface ships are engaged by the Blue DDGs only. Upon detection of Red surface contact, two DDGs are dispatched to engage them. They rejoin their patrolling areas upon completion of their mission. The DDGs operate in parallel to the MDUSVs as shown in Figure 18, thereby providing them protection against Red's ASCM.

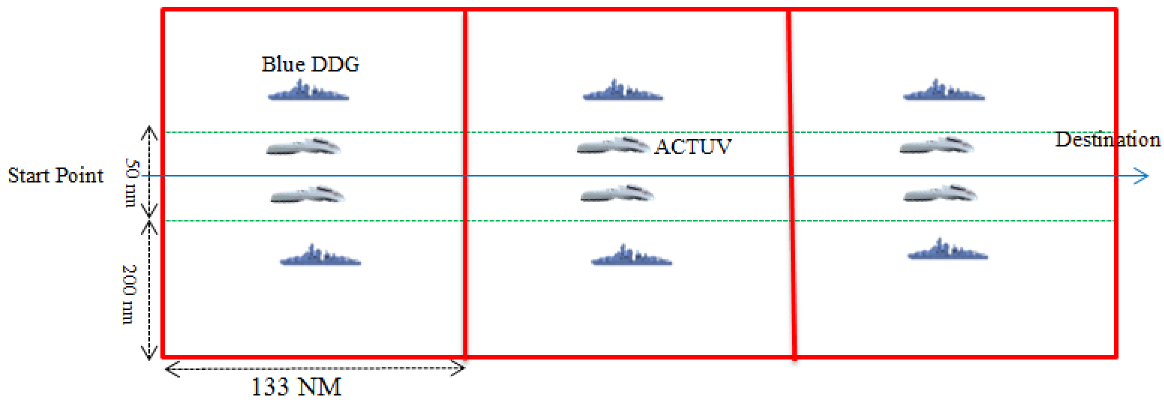


Figure 18. Zone defense model with MDUSVs.

4. Scenario 32

Scenario 32 is similar to scenario 31 except that it has an additional support of two TERNs. TERNs are used in the same role as in the close escort model. Upon classification of Red surface ships, a TERN shares the information with all the Blue DDGs. Blue then detaches three DDGs to engage the Red surface ships. They rejoin their patrol area upon success.

5. Scenarios 33–36 (Red Submarine Tactic-2)

These scenarios are similar to scenarios 29–32 respectively, but now the Red submarine will use its tactic 2 of weapon employment in the model—preferring to attack with missile followed by torpedo attack. This weapon priority tactic is applied against the convoy ships only. Red submarines will prefer torpedo attack against Blue combatants while in a zone defense area.

IV. DESIGN OF EXPERIMENT

A. MEASURE OF EFFECTIVENESS

A simulation study's foremost decision is to select appropriate measures of effectiveness (MoEs) that are directly related to the study's objective. The MOEs form the analytical basis to gain insights from the model. Our study's objective was to develop a convoy defense to minimize the expected number of convoy ship losses in a specific scenario. The convoy comprised 10 cargo vessels and the MOE selected was "expected number of convoy ships killed." Data was also collected for the number of convoy ships killed by surface ships and submarines to compare the lethality of the two Red platforms.

B. MEASURES OF PERFORMANCE

Measures of performance (MOPs) are the attributes or factors of the different agents, which when varied affect the output (expected number of casualties of convoy ships). These are explained in the ensuing paragraphs:

(1) Blue Defense Options

Blue has two defense options: close escort operation and zone defense assignments. These were translated into different scenarios as explained in Chapter II. The output of each model was analyzed for the MoE in comparison to the others.

(2) Weapon Ranges

The maximum ranges of missiles and torpedoes on Blue surface ships were varied while keeping their associated SSKPs constant. The weapon ranges were considered as a factor because we want to find their minimum required ranges for effective convoy protection.

(3) Single Shot Kill Probabilities

The single shot kill probabilities (SSKPs) of all the weapons of Blue surface ships were varied while keeping their maximum ranges constant. One can expect that higher

SSKPs will provide the best defense, but we were also interested in their optimum requirements for effective protection of the convoy.

(4) Sensor Ranges

Maximum ranges of all the sensors of Blue surface vessels were varied while keeping their probabilities of detection and classification constant.

(5) Probabilities of Detection by Sensors

All the sensor probabilities of detection and classification of Blue surface vessels were varied while keeping their maximum ranges constant.

(6) Red Submarine Weapon Priorities

The red submarines carry missiles and torpedoes. Submarines have the option to approach the convoy and attack with torpedoes first, or attack first at longer range with missiles. Each option has its own risks and rewards for the submarine, which we wished to quantify through our study. This factor is embedded in the scenarios as mentioned in Chapter III.

(7) Tactically Exploited Reconnaissance Node

We wanted to analyze the impact of employment of TERN in the different scenarios. This factor (having TERNs or not) is also embedded in the scenarios explained in Chapter III.

(8) Medium Displacement Unmanned Surface Vessel

MDUSVs were varied in number as well as deployment tactics in the scenarios. Their impact on the MOE was assessed based on their number and deployment tactics.

(9) Number of Surface-to-Air Missiles on Blue DDGs

SAM inventory onboard Blue DDGs was varied between 10 and 100 to find their optimum number for use in a missile and torpedo threat environment.

(10) Red Submarine Concealment

The concealment factor was used to model the relative quietness of the submarine and changing acoustic environment affecting surface ship sonar performance. A surface ship or other platform searching for a submarine uses active and/or passive sonars that work on the echo-ranging principle. In passive mode, sonar detects the radiated noise of the target and determines its direction. Therefore, detection of a target is directly associated with the quietness of the target (Red submarine in this case). In active mode, sonar transmits sound waves, which if hit a target return to the source (transmitting platform). These sound waves are processed and target range and direction are determined. It therefore requires reflection of the transmitted sound waves from the target to be detected-.

It is difficult to detect a quieter submarine and difficult if the transmitted sound waves do not reflect from the target towards the source. The latter phenomenon is associated with the ocean's acoustic environment, which is not uniform and varies with pressure (depth) and temperature (geographical area and/or depth). The deep ocean environment may be divided into three acoustic layers (mixed, thermocline and deep water), as shown in Figure 19. The depth of the thermocline layer is different for different regions and oceans. The submarine would prefer to be undetected all the time and remain in the shadow zone (thermocline layer). The submarine's passive detection and classification ranges are also reduced in this zone, however. Additionally, it needs to come to periscope depth for target confirmation and firing of weapons. Therefore, submarine concealment depends on many considerations—not all known by Blue forces. We varied concealment to see how different defensive formations may impact convoy ship protection with different submarine quietness and acoustic conditions.

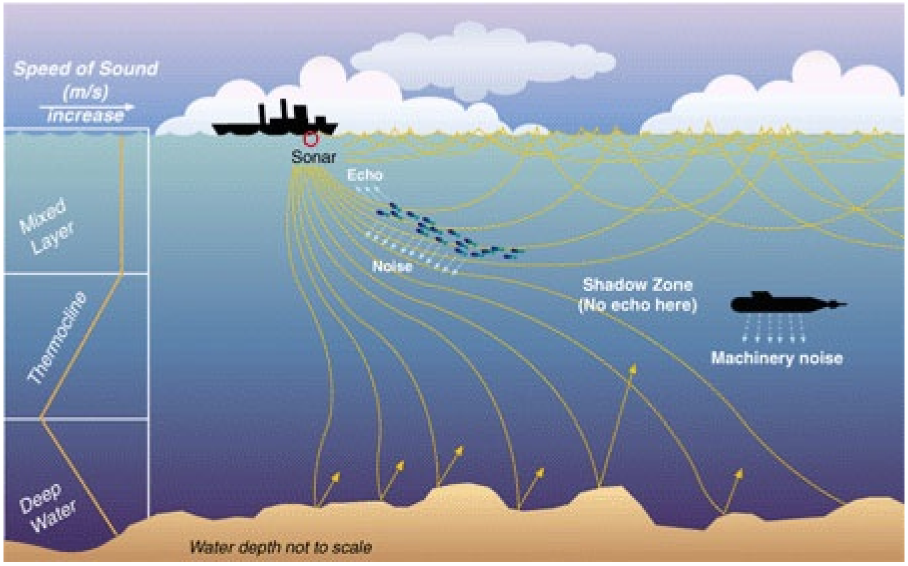


Figure 19. Acoustic layers of the ocean (Source: http://www.dosits.org/images/dosits/history-shadowzone.jpg).

The factors and their variation ranges are summarized in Table 20.

Table 20. Requirements of DOEs.

S No	Wpn/Sensor	Range	Remarks
1.	Scenario/Formation	1–36	Categorical. Only one formation at a time out of the 36.
2.	Missile max range	1,0.75,0.5,0.25	Discrete factor
3.	Torpedo max range	1,0.75,0.5,0.25	-’’-
4.	Sonar max range	1,0.75,0.5,0.25	-’’-
5.	Radar max range	1,0.75,0.5,0.25	Same as above
6.	Missile SSKP	1,0.75,0.5,0.25	-’’-
7.	Torpedo SSKP	1,0.75,0.5,0.25	-’’-
8.	Sonar prob. of detection/classification	1,0.75,0.5,0.25	-’’-
9.	Radar prob. of detection/classification	1,0.75,0.5,0.25	-’’-
10.	Number of SAMs	10–100	Discrete factor
11.	Red Tactics	1,2	Categorical. Only one tactic is applied at a time but to all the scenarios/formations.
12.	Red Submarine Concealment	0.2–0.7	Continuous factor with a step size of 0.1

C. NEARLY ORTHOGONAL LATIN HYPERCUBE DESIGN

A full factorial design would need $36 \times 4^8 \times 90 * 5$ = 1,061,683,200 (1061 million) design points. Each design point takes 15 minutes on average to execute on a personal computer. It would require 30,300 years to complete a full factorial design on a personal computer. Assuming a super computer is 1,000 times faster than a PC, it would require 30 years to complete the experiment. Therefore, we needed a smarter way of designing the experiment to reduce the number of design points and still be able to analyze sufficient breadth of the outcomes.

Susan Sanchez (2011) provided a solution to the problem through published design aid spreadsheets. We used the nearly orthogonal Latin hypercube (NOLH) design worksheet for this study. NOLHs were designed (Cioppa and Lucas, 2007) to efficiently sample high-dimensional spaces with designs that are nearly orthogonal (hence, have good statistical properties) and have good space-filling properties (i.e., have minimal unsampled regions). Moreover, they allow analysts to fit a breadth of diverse metamodels to the output. A broader set of NOLHs can be found in Hernandez et al. 2012. For complete second order NOLHs, see MacCalman et al. 2017.

NOLH provides good space-filling properties and meets the orthogonality criteria required for a good DOE, as shown in Figure 20’s scatter plot matrix. We divided the simulation into two experiments. In one, we fixed the probabilities and changed the ranges, whereas in the other we fixed ranges and varied probabilities. The NOLH Design reduced the overall design points to 4644 × 2. Each design point was replicated 60 times resulting in a standard error of 0.20 to 0.30 per design point. The simulation run time was therefore reduced to 97 days on a personal computer and 2.3 hours on our hypothetical super computer. Implementing this design on the NPS cluster computer took around 14 days to complete all simulations, which provided sufficient insights into the model required for the study. The design of experiment’s NOLH output is included in the appendix.

Multivariate

Correlations

	Submarine.Concealment	Escort.Missile.Range.multiplier	Escort.Torpedo.Range.multiplier	Escort.Radar.Range.multiplier	Escort.Sonar.Range.multiplier	Escort.AntiAir.Missiles
Submarine.Concealment	1.0000	-0.0146	-0.0224	-0.0356	-0.0229	0.0007
Escort.Missile.Range.multiplier	-0.0146	1.0000	0.0021	0.0021	0.0021	0.0643
Escort.Torpedo.Range.multiplier	-0.0224	0.0021	1.0000	0.0021	0.0021	-0.0192
Escort.Radar.Range.multiplier	-0.0356	0.0021	0.0021	1.0000	0.0021	0.0161
Escort.Sonar.Range.multiplier	-0.0229	0.0021	0.0021	0.0021	1.0000	0.0124
Escort.AntiAir.Missiles	0.0007	0.0643	-0.0192	0.0161	0.0124	1.0000

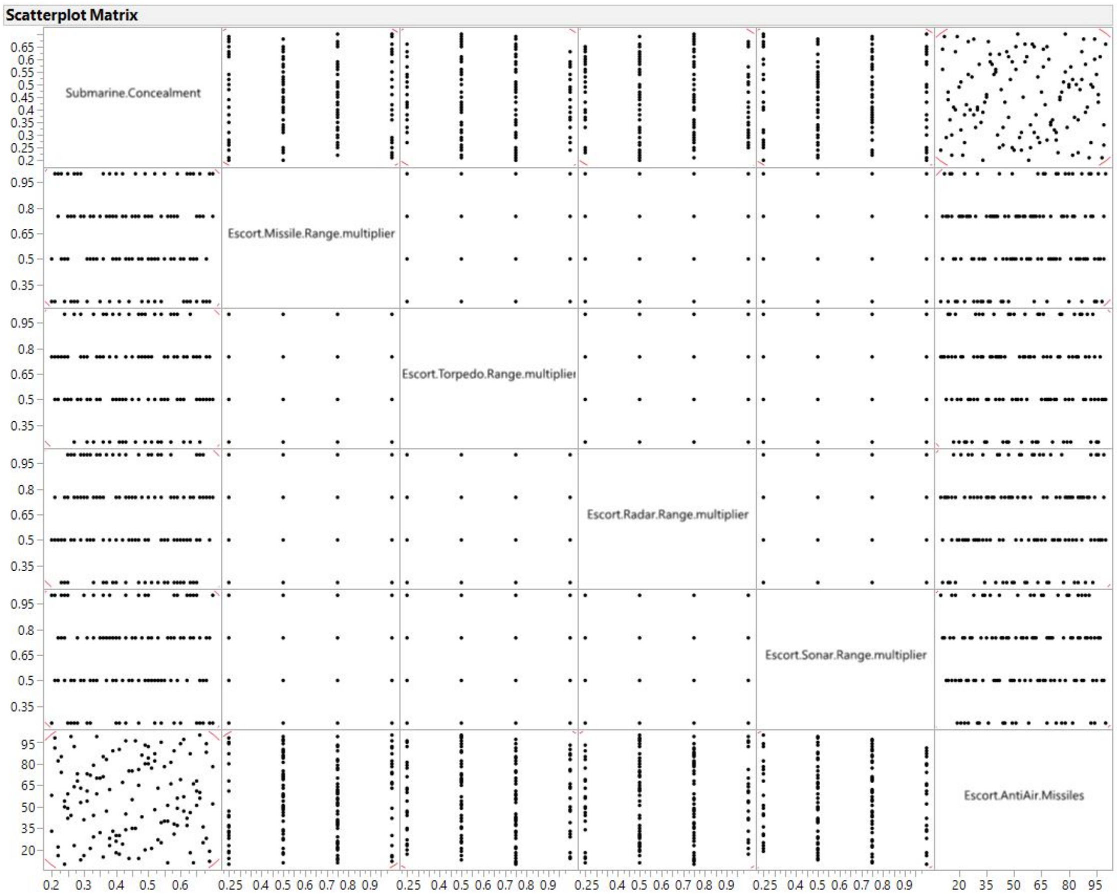


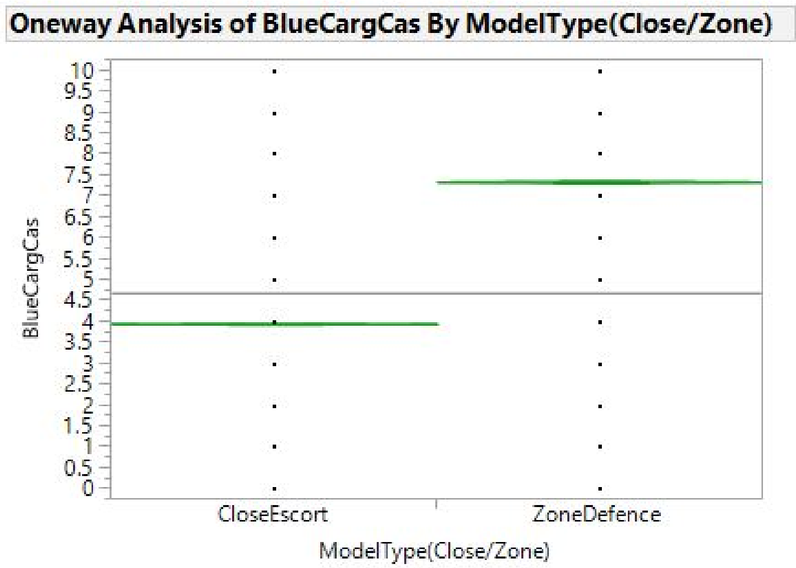
Figure 20. NOLH design of experiment — scatter plot matrix.

V. DATA ANALYSIS

This chapter provides analysis of the results obtained from our simulations. It first compares the overall performance of the two basic models: zone defense and close escorts operations. After clearly showing the close escort option's superiority, we take a more detailed look at the close escort model variants and the two Red submarine's weapon employment tactics. Thereafter, we carry out sensitivity analysis of the models through regression and partition tree analysis. Finally, we look for the optimum capabilities (weapon and sensors characteristics) of Blue combatants for effective protection of the convoy through analysis of the individual factors.

A. GENERAL RESULTS

The close escort model significantly outperforms the zone defense model across all simulations. In the convoy size of 10, expected casualties of cargo ships are 3.954 [3.938, 3.972] in the close escort model and 7.35 [7.317, 7.382] in the zone defense model, as shown in Figure 21. Thus, the close escort model is almost twice as effective as the zone defense model across all model variations. Radar range is the most important factor in determining the output of the model, followed by the numbers of SAMs onboard Blue DDGs, if they are less than 30. When the radar range is greater than 30 NM and number of SAMs onboard each DDG is greater than 30, the Blue capabilities related to finding and killing submarines becomes important in driving the output. All this implies that convoy defense in a multi-dimension threat is first an air defense problem against modern anti-ship cruise missiles.



Oneway Anova

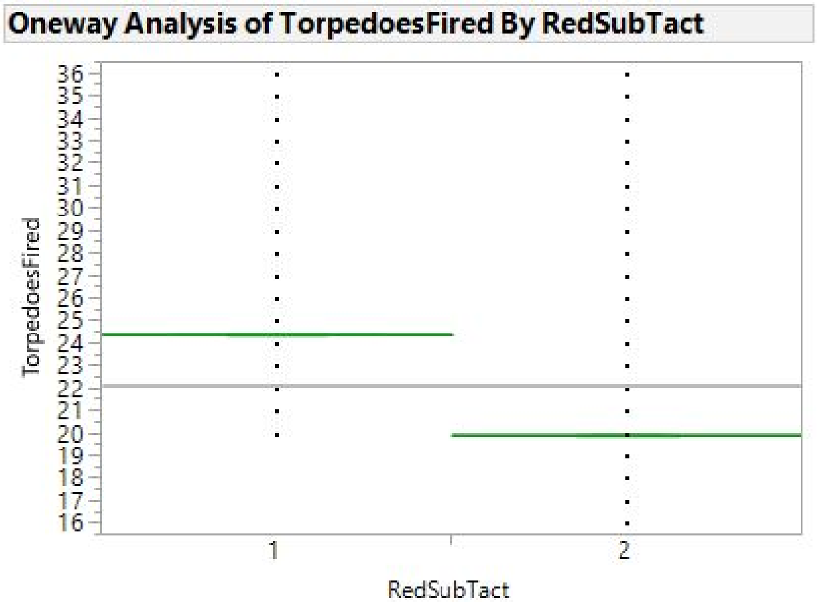
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
CloseEscort	216720	3.95473	0.00876	3.9376	3.9719
ZoneDefence	61920	7.34952	0.01639	7.3174	7.3816

Std Error uses a pooled estimate of error variance

Figure 21. Losses of convoy ships in "close escort" is almost half of losses incurred by using a "zone defense" tactic.

The submarine obtains more hits on Blue cargo vessels if its priority tactic is to fire a missile salvo first and then torpedoes (RedSubTact2). The expected hits on Blue cargo vessels are 4.1 [4.08, 4.13] in RedSubTact2 against 3.8 [3.78, 3.83] in RedSubTact1. The results do not account for the additional lethality of a torpedo hit when compared to an ASCM hit; however, torpedoes are designed to sink large surface ships, whereas an ASCM may hit a large container ship with little permanent damage. Figure 22 shows that Red submarines fire approximately 25 torpedoes out of 36 in RedSubTact1 and only 20 when using RedSubTact2. This means that further exploration is required as to Red submarine weapon priority as MANA limitations prevent modeling different lethality of weapons against the same target.



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	108360	24.4375	0.01375	24.411	24.464
2	108360	19.9656	0.01375	19.939	19.993

Std Error uses a pooled estimate of error variance

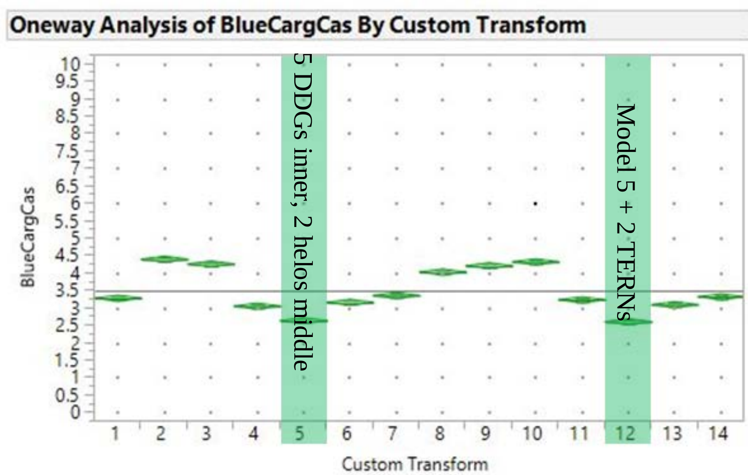
Figure 22. Torpedoes fired by the Red submarines in different tactics of weapon priority. Red submarines average almost five more torpedo attacks using a "torpedo first" tactic than when attacking with missiles first.

B. ANALYSIS OF SCENARIOS

In this section, we analyze the effectiveness of different tactics and scenarios with regard to the response variable (expected number of casualties of Blue cargo vessels). Since the zone defense model's performance is dominated by the close escort model, we focus our analysis on the variants of the close escort model. These include scenario 1 through scenario 14 for RedSubTact1 (torpedo first) and scenario15 through scenario 28 for RedSubTact2 (missile first). Scenarios 15 through 28 are exact replicates of scenarios 1 through 14 except that they are tested against the different weapon employment tactics of Red submarines. Our aim is to find the most robust scenario based on the controllable factors (factors related to Blue force) which would minimize the expected casualties of Blue cargo vessels.

1. Scenarios 1–14 (RedSubTact1 — Torpedo First)

When the Red submarine uses torpedoes as its priority weapon, the Blue convoy suffers fewer expected casualties in scenarios 5 and 12 (i.e., 2.65 [2.572, 2.741] and 2.62 [2.54, 2.71], respectively) which are statistically insignificant at 95% significance level. The model of scenario 5 comprises two helicopters in the intermediate screen and five DDGs in the inner screen. The model of scenario 12 is similar to that of scenario 5 except that it has an additional support of two TERNs in ISR role. These results confirm that, tactically, for a Red submarine to position itself for a torpedo attack, it must expose itself more often to search units if an intermediate screen is populated. Figure 23 depicts these results.



Oneway Anova

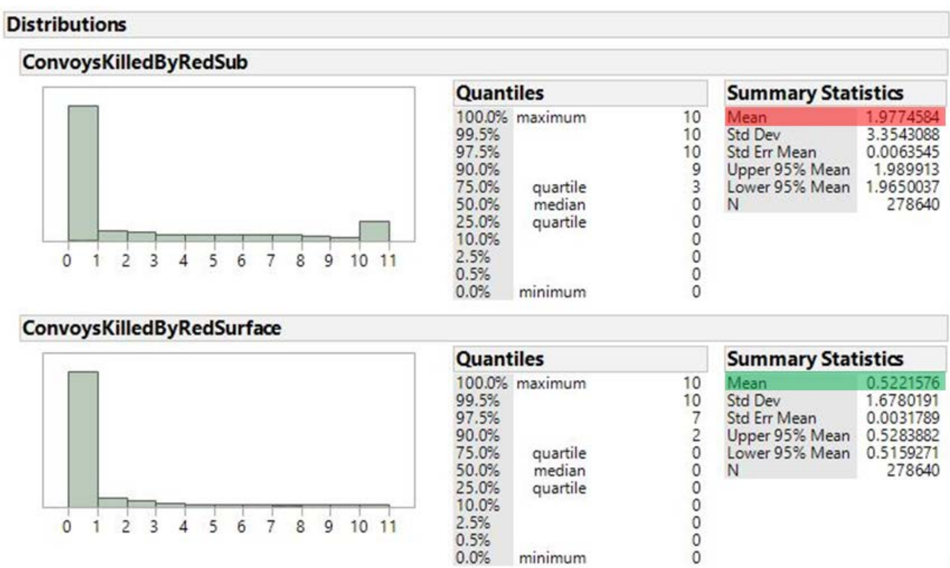
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	7740	3.30065	0.04319	3.2160	3.3853
2	7740	4.41873	0.04319	4.3341	4.5034
3	7740	4.28282	0.04319	4.1982	4.3675
4	7740	3.07339	0.04319	2.9887	3.1580
5	7740	2.65646	0.04319	2.5718	2.7411
6	7740	3.18075	0.04319	3.0961	3.2654
7	7740	3.37700	0.04319	3.2923	3.4617
8	7740	4.04987	0.04319	3.9652	4.1345
9	7740	4.22920	0.04319	4.1445	4.3139
10	7740	4.34328	0.04319	4.2586	4.4279
11	7740	3.25310	0.04319	3.1684	3.3378
12	7740	2.62481	0.04319	2.5401	2.7095
13	7740	3.11525	0.04319	3.0306	3.1999
14	7740	3.34173	0.04319	3.2571	3.4264

Std Error uses a pooled estimate of error variance

Figure 23. Casualties of Blue cargo vessels in Scenarios 1–14 with one-way analysis of variance (ANOVA) on their mean: The Blue convoy suffers fewer casualties in scenarios 5 and 12.

Red submarines do not have the capability of attacking helicopters, so the scenarios comprising ASW helicopters are expected to perform better than the others. Additionally, they offer very little chance to Red DDGs to detect and kill them due to their small radar cross-section areas and low-flying abilities. In short, they carry out ASW operations in a minimal threat environment. On the other hand, if a helicopter detects a submarine, it shares the information with the second helicopter and they both continue their attack on the target submarine until it is killed. This way, a submarine detected by a helicopter is killed most of the time. The uncertainty comes into play when both helicopters fire their torpedoes on the target and miss it. The helicopters then take 2 hours 45 minutes to rearm, during which time the submarine has chances to escape the attack. Additionally, Red submarines cause more hits on Blue convoy than the Red DDGs, as shown in Figure 24. Among the scenarios containing helicopters, the ones with intermediate screen perform better against RedSubTact1 (torpedo as priority weapon of employment for Red submarine), because the submarine has relatively less room between the helicopters and convoy to penetrate into the screen for torpedo attack.

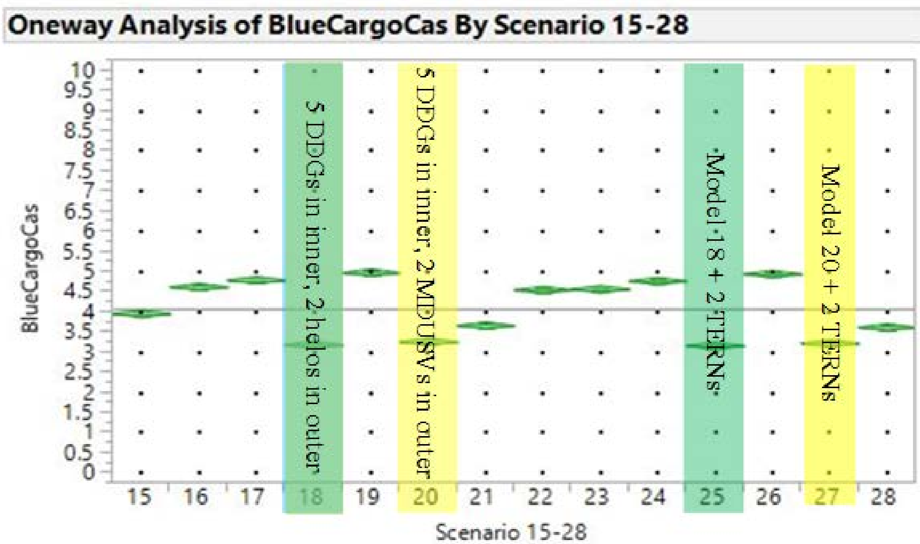


The top distribution shows the convoy ships hit by Red submarines and the lower one shows those killed by Red DDGs. The Red submarines account for almost four times as many convoy casualties as the Red DDGs.

Figure 24. Distribution of casualties of Blue cargo ships per Red shooter platform.

2. Scenarios 15–28 (RedSubTact2 — ASCM First)

When the Red submarine sets ASCM as its priority weapon for employment against the Blue convoy, layered defense with the ASW helicopters in the outer screen with or without TERNs suffer fewer expected casualties of cargo vessels. This is closely followed by the model in which the helicopters are replaced by the MDUSVs with two DDGs in the outer screen. They are statistically indifferent at significance level of .05, as shown in Figure 25.



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
15	7740	3.96512	0.04490	3.8771	4.0531
16	7740	4.63230	0.04490	4.5443	4.7203
17	7740	4.80155	0.04490	4.7136	4.8895
18	7740	3.19444	0.04490	3.1064	3.2824
19	7740	4.98889	0.04490	4.9009	5.0769
20	7740	3.26925	0.04490	3.1813	3.3572
21	7740	3.67274	0.04490	3.5847	3.7607
22	7740	4.55775	0.04490	4.4698	4.6457
23	7740	4.57636	0.04490	4.4884	4.6644
24	7740	4.77972	0.04490	4.6917	4.8677
25	7740	3.16990	0.04490	3.0819	3.2579
26	7740	4.95491	0.04490	4.8669	5.0429
27	7740	3.23269	0.04490	3.1447	3.3207
28	7740	3.62829	0.04490	3.5403	3.7163

Figure 25. Performance of scenarios 15–28 (RedSubTact2) with one-way analysis of variance on mean of Blue cargo vessels.

It is worth highlighting that the best options of defense against the RedSubTact2 involve layered defense with outer screen. We believe this is due to Red submarines being engaged by the outer screen units before they launch any ASCMs. The intermediate screen models underperform the outer screen ones because the ASCM range of the Red submarine is more than 40 NM, whereas the intermediate screen is employed at 25–30 NM from the convoy. Thus, the Blue units in an intermediate screen can only engage the Red submarine after it has carried out missile attack on the convoy. Therefore, if helicopters are available and we believe the submarine will attack first with missiles, the helicopters should be assigned an outer screen position. Conversely, if we believe the submarine will close for torpedo attack first, assigning helicopters in an intermediate screen is preferred.

C. SENSITIVITY ANALYSIS

In this section, we analyze the effect of each controllable and uncontrollable factor on the response variable (expected number of casualties of Blue cargo vessels). Controllable factors in the study are Blue force capabilities and characteristics, whereas uncontrollable factors are the Red submarine's tactics of weapon employment and its concealment factor. The controllable factors include number of missiles, ranges of weapons and sensors, detection probabilities of sensors and single-shot kill probabilities of weapons.

Since we are using range-dependent probabilities, the ranges and accuracies of weapons and sensors required separate DOEs, each resulting in 4,644 design points (DPs) using NOLH design spreadsheet. In the first experiment (referred to as "Experiment 1" from here onward) we varied the ranges of weapons and sensors as well as number of SAMs and Red submarine's concealment factor. In the second experiment (referred to as "Experiment 2" from here onward), we varied the detection probabilities of sensors, SSKPs of weapons, number of SAMs onboard each Blue DDG and submarine's concealment factor. The importance of a factor in each category is determined through its contribution to the regression and partition tree models. It also helped in determining

whether range of a sensor or weapon or its probability of detection or kill is more important.

1. Regression Analysis — Experiment 1

The maximum ranges of weapons and sensors for Blue escorts are given degradation factors over four levels (1.0, 0.75, 0.5 and 0.25) and number of SAMs onboard DDGs are varied from 10 to 100. Regression and partition tree analysis were conducted for model sensitivity to these factors. Response variable in both is the expected Blue cargo vessels casualties while ranges of weapons and sensors and number of surface-to-air missiles (SAMs) are used as predicting variables.

The multiple regression model in Figure 26 shows a lot of interactions between the predicting terms, which is expected as the weapons and sensors are interdependent with regard to the MoE. The steepness of slopes in the prediction profile indicates the level of significance of the particular factor for a particular range. All the factors are found to be statistically significant but the air defense factors related to defeating ASCMs, such as radar range, surface-to-air missile ranges and number of surface-to-air missiles onboard each DDG, are found to be the overriding ones if they are below certain limits. This suggests the relative importance of air defense over underwater defense if the DDGs are not sufficiently equipped to defeat ASCMs. It also indicates the optimum ranges of weapons and sensors of DDGs for effective convoy protection against the given threat. The factors are mentioned below.

Range of radar: 30 NM

Range of SAMs: 30 NM

Number of SAMs: 35

Long-range torpedoes

Long-range sonars

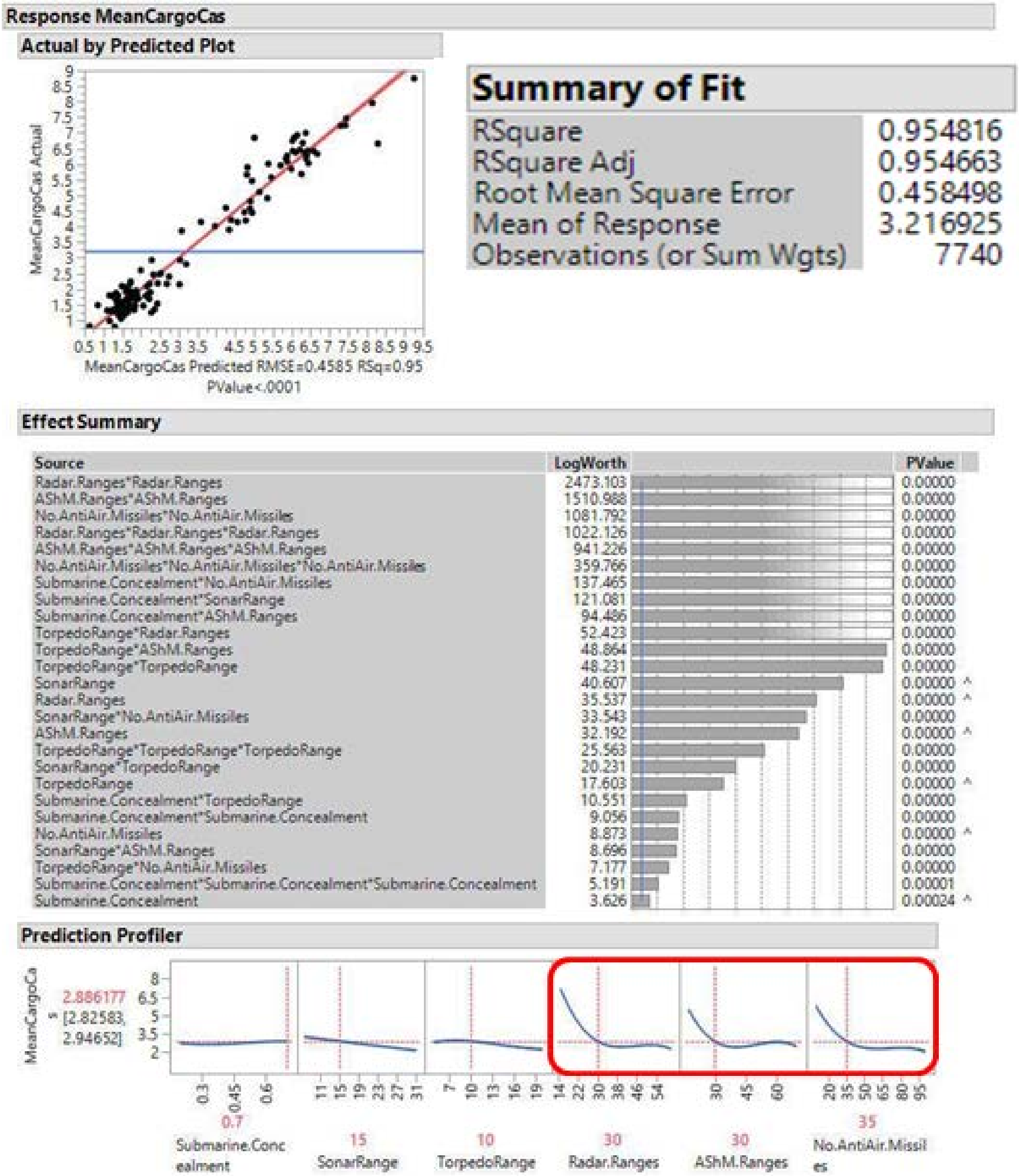


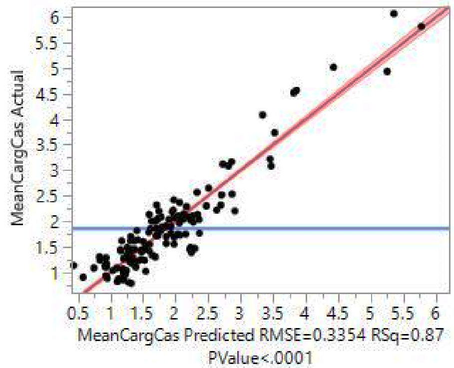
Figure 26. Regression model for "expected casualties of convoy ships" with ranges of weapons and sensors, number of SAMs and Red submarine concealment as predicting variables.

2. Regression Analysis — Experiment 2

Similar to ranges, the probabilities of detection and kill of sensors and weapons, respectively, were also varied using four levels of degradation (0.25, 0.5, 0.75 and 1.0 of maximum values) while keeping their maximum ranges constant as mentioned in Chapter III. An important thing to note is that the probabilities of detection and classification of radar and sonar as well as the SSKP of torpedo are range dependent. Other variable factors in the model include number of SAMs onboard each DDG and Red submarine's concealment. The multiple regression model in Figure 27 shows that all the factors are important. When the prediction profile is compared with that of the regression model of Experiment 1, it is observed that the detection probability of radar as well as SSKP of SAMs are less important than their ranges. It also shows that underwater and air defense factors carry equal importance in the model in terms of probability of detection and kill.

Response MeanCargCas

Actual by Predicted Plot



Summary of Fit

RSquare	0.871779
RSquare Adj	0.871346
Root Mean Square Error	0.335391
Mean of Response	1.871441
Observations (or Sum Wgts)	7719

Effect Summary

Source	LogWorth	PValue	
Escort.AntiAir.Missiles*Escort.AntiAir.Missiles	1126.207	0.00000	
Escort.AntiAir.Missiles*Escort.AntiAir.Missiles*Escort.AntiAir.Missiles	982.887	0.00000	
AShM.SSKP.Factor*Escort.AntiAir.Missiles	486.917	0.00000	
AShM.SSKP.Factor	438.576	0.00000	^
Torpedo.SSKP.Factor	354.050	0.00000	
Escort.AntiAir.Missiles	219.485	0.00000	^
Sonar.Det.Prob.Factor	153.563	0.00000	
Submarine.Concealment*Submarine.Concealment	136.425	0.00000	
Sonar.Det.Prob.Factor*Torpedo.SSKP.Factor	97.840	0.00000	
Radar.Det.Prob.Factor*AShM.SSKP.Factor	88.775	0.00000	
Submarine.Concealment*Torpedo.SSKP.Factor	84.210	0.00000	
Radar.Det.Prob.Factor*Radar.Det.Prob.Factor	83.183	0.00000	
Sonar.Det.Prob.Factor*Sonar.Det.Prob.Factor	66.713	0.00000	
Submarine.Concealment*Escort.AntiAir.Missiles	56.241	0.00000	
Sonar.Det.Prob.Factor*Sonar.Det.Prob.Factor*Sonar.Det.Prob.Factor	41.284	0.00000	
Radar.Det.Prob.Factor*Radar.Det.Prob.Factor*Radar.Det.Prob.Factor	40.280	0.00000	
Radar.Det.Prob.Factor*Escort.AntiAir.Missiles	30.998	0.00000	
Submarine.Concealment*AShM.SSKP.Factor	15.340	0.00000	
Submarine.Concealment	12.262	0.00000	^
Torpedo.SSKP.Factor*Radar.Det.Prob.Factor	12.166	0.00000	
Torpedo.SSKP.Factor*AShM.SSKP.Factor	10.158	0.00000	
Submarine.Concealment*Radar.Det.Prob.Factor	10.082	0.00000	
Radar.Det.Prob.Factor	7.169	0.00000	^
Torpedo.SSKP.Factor*Escort.AntiAir.Missiles	5.896	0.00000	
Sonar.Det.Prob.Factor*Radar.Det.Prob.Factor	4.971	0.00001	
Submarine.Concealment*Submarine.Concealment*Submarine.Concealment	3.250	0.00056	

Prediction Profiler

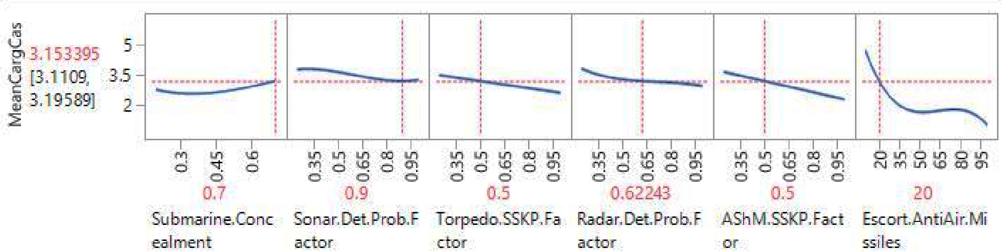


Figure 27. Regression model for “expected casualties of convoy ships” with probabilities of detection sensors, SSKP of weapons, number of SAMs and Red submarine concealment as predicting variables.

3. Partition Tree — Experiment 1

The partition tree in Figure 28 also suggests that air defense capabilities of the convoy escorts need to be prioritized over the underwater capabilities until and unless the minimum air defense capabilities in terms of ranges are met. The first split occurs at “Radar range” greater or less than 30 NM with large difference in the response variable considering the convoy size of 10: 2.5±1.65 if greater than 30 NM and 6.65±0.69 if less than 30 NM. The second split occurs at “SAM ranges” greater or less than 35 NM with almost similar impact on the response variable. The remaining five splits occur on the “Numbers of SAMs” onboard each DDG. The seven splits model explains approximately 88% of variance of the model with all the factors of air defense. The contribution of each factor towards the predicting-model is also captured in Figure 29. Surprisingly, the underwater defense factors (ranges of sonar and torpedo as well as submarine concealment) have zero contributions, whereas almost 50% of the model’s predicting power is attributed towards the radar’s ranges. It is worth highlighting here that the radar ranges are applicable to both the surface (used for detecting the Red surface platforms) and air search radars (used for detecting and acquiring the Red incoming missiles), which directly influence the firing ranges of ASCMs and SAMs. Therefore, it is intuitive to say that the radar range is the most influential factor in the air defense part of the model. The underwater defense factors start gaining importance in the model after the minimum requirements for air defense are met and are captured in Figure 30. Detail of the factors’ importance in the model is explained in the subsequent paragraphs.

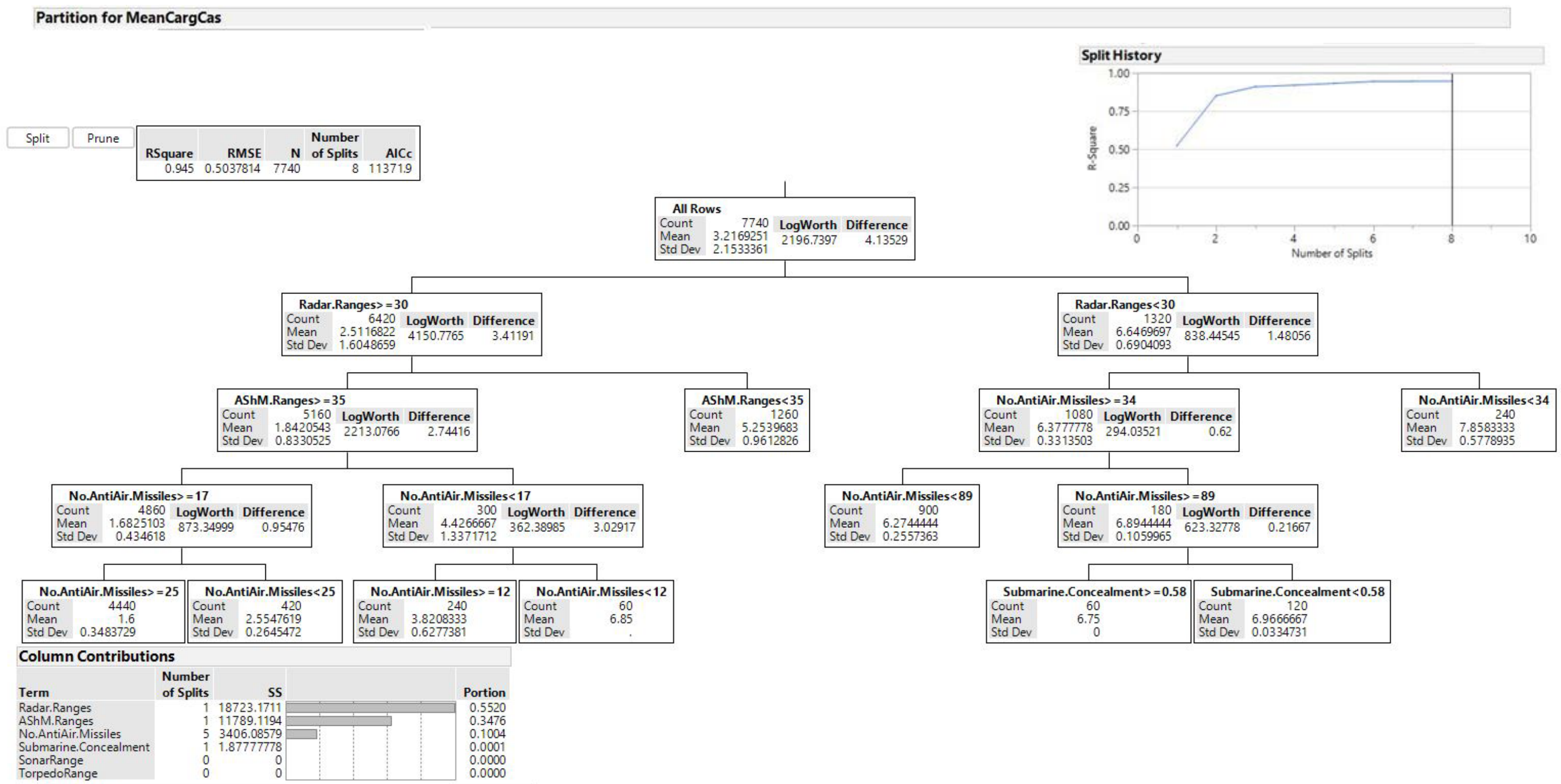
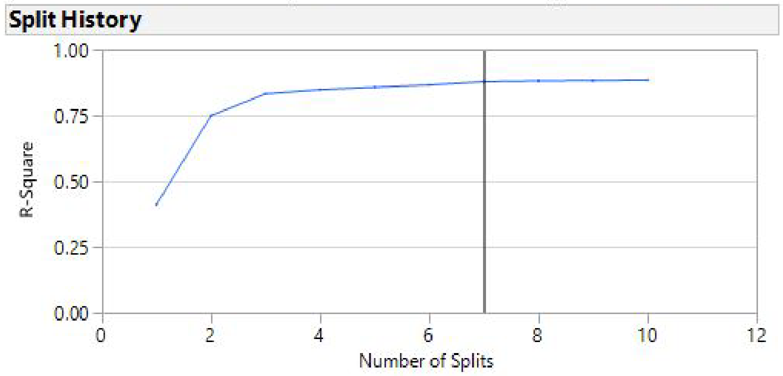


Figure 28. Partition tree for predicting the expected casualties of Blue cargo vessels with ranges of sensors and weapons, number of SAMs and Red submarine's concealment as predicting variables.



Column Contributions

Term	Number of Splits	SS	Portion
Escort.Radar.Range.multiplier	1	563751.627	0.4679
Escort.Missile.Range.multiplier	1	463828.38	0.3849
Escort.AntiAir.Missiles	5	177393.03	0.1472
Escort.Torpedo.Range.multiplier	0	0	0.0000
Escort.Sonar.Range.multiplier	0	0	0.0000

Figure 29. Split history of the decision tree for predicting the expected casualties of Blue cargo vessels: Highlighting R-Square and factors' contribution to the model.

Custom Split: SAM>35,Radar Rng>=30,SAM Rng>30

Column Contributions

Term	Number of Splits	SS	Portion
Submarine.Concealment	11	89.3119753	0.4586
No.AntiAir.Missiles	3	31.4055556	0.1613
SAM.Ranges	1	30.2547003	0.1554
TorpedoRange	1	19.1852729	0.0985
Radar.Ranges	1	15.897963	0.0816
SonarRange	3	8.69064815	0.0446

Figure 30. Factors' contribution to the model with the SAM, radar ranges greater than 30 NM and number of SAMs greater than 35 on each Blue DDG.

4. Partition Tree — Experiment 2

The model in Figure 31 suggests that the sonar's probability of detection and SSKP of torpedo are very significant in predicting the output of the model, which was not the case when we were analyzing their range effect. Overall, they contribute 33% towards

the predicting power of the model, as shown in Figure 32, but were 0% in the earlier one. This also indicates that detection probability of sonar and SSKP of torpedo are more important than their ranges.

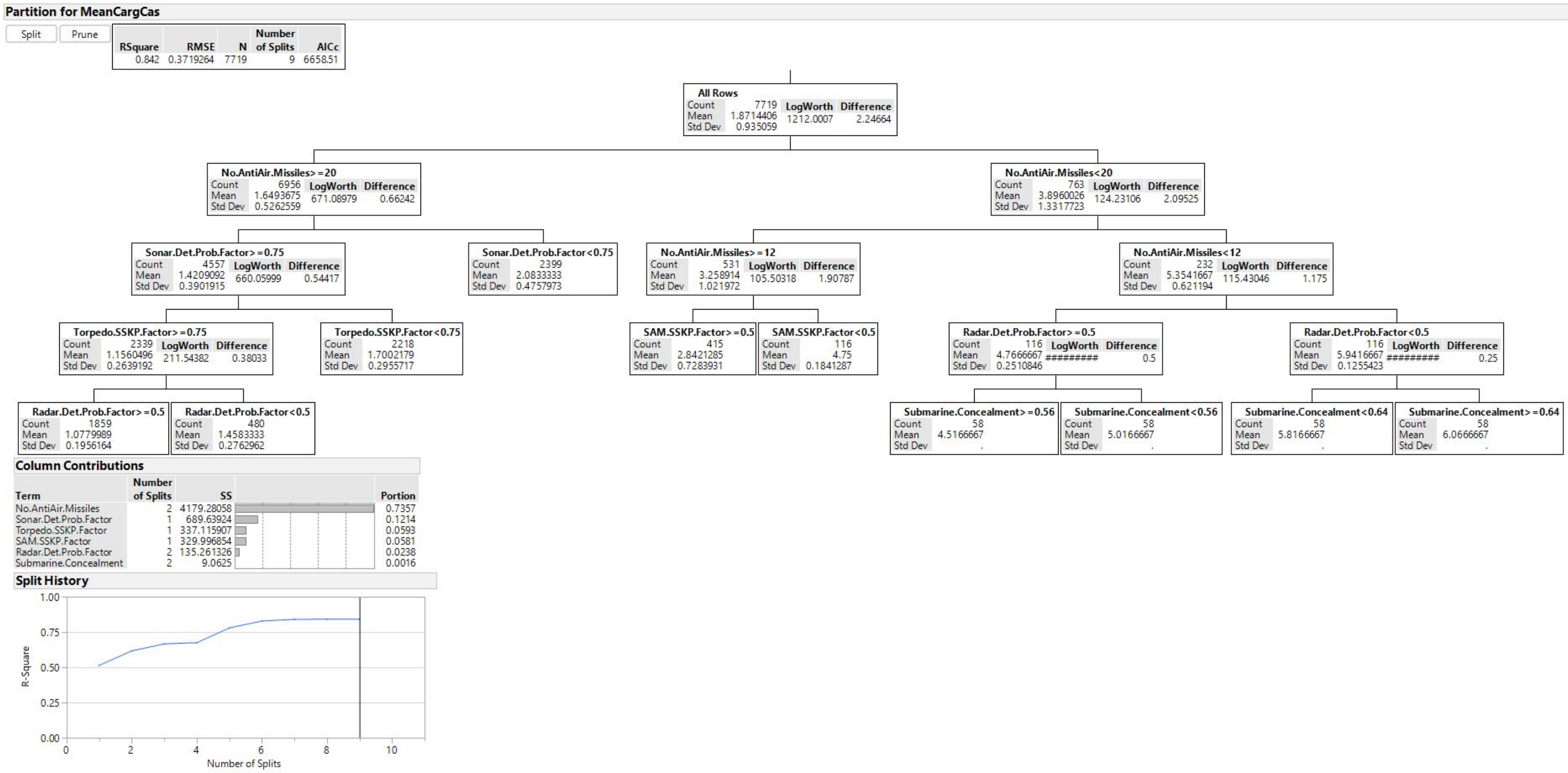
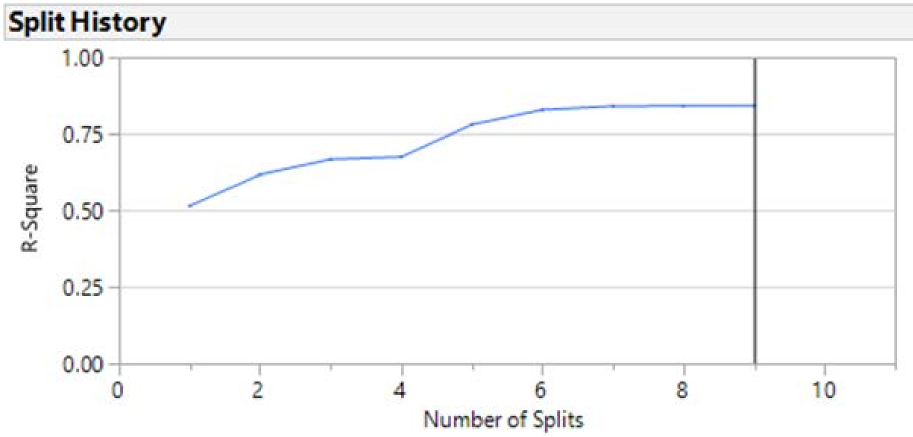


Figure 31. Decision tree for predicting the expected casualties of Blue cargo vessels with regard to probabilities of factors as predicting variables.



Column Contributions

Term	Number of Splits	SS	Portion
No.AntiAir.Missiles	2	4179.28058	0.7357
Sonar.Det.Prob.Factor	1	689.63924	0.1214
Torpedo.SSKP.Factor	1	337.115907	0.0593
SAM.SSKP.Factor	1	329.996854	0.0581
Radar.Det.Prob.Factor	2	135.261326	0.0238
Submarine.Concealment	2	9.0625	0.0016

Figure 32. Contribution of factors towards predicting power of the model.

By combining the results of regression models of the two experiments, the minimum capabilities of escorts can be generalized. Long-range radars and SAMs with above average detection probabilities and SSKP, sufficient number of SAMs per DDG, long-range torpedoes with high SSKP and long-range sonars with above average detection probabilities are considered optimum in defending the convoy effectively against the given threat.

D. FACTOR BY FACTOR ANALYSIS

In this section, we analyze the individual factors both in terms of their ranges and probability of detection and kill wherever applicable.

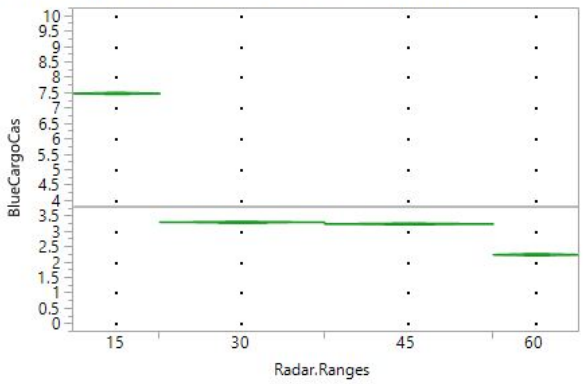
1. Radar

Radar range and probability of classification were varied by degradation factors (0.25, 0.5., 0.75, and 1) of their maximum values with the radar probability of classification as range dependent. Accordingly, any change in radar probability indicates

changes in all the probabilities associated with the ranges. Keeping the probability factor constant at maximum values, we found that the radar range is most important in defending the convoy ships against the given threat. The expected losses of Blue cargo vessels increased from 2.27 [2.24, 2.31] to 7.51 [7.48, 7.55] (an overall change of more than 350%) with the decrease of radar detection ranges, but not linearly, as shown in Figure 33. Figure 33 shows that the expected losses increased to 7.51 [7.476, 7.548] from 3.33 [3.30, 3.35] (an increase by 125%) when the radar detection range was reduced from 30 to 15. Therefore, radar detection range of 30 NM or less is considered to be critical in determining the success of convoy protection in the model. The factor seems to be very less significant between the ranges of 30 and 45 NM in the presence of other factors of the model. Further increase of the factor to 60 NM significantly reduced the expected losses of Blue cargo vessels. The factor is therefore considered to be critical between the ranges of 15 to 30 NM and 45 to 60 NM.

On the other hand, when we kept the radar range at maximum and varied the probabilities, we found its similar effects on the response variable, but in a much more linear way between 50–75 % as compared to its ranges, as shown in Figure 34. The expected losses were reduced to 0.69 [0.67, 0.72] from 2.58 [2.55, 2.6], with overall improvement of more than 350%. This indicates that probability of classification of radar is as important as its range.

Oneway Analysis of BlueCargoCas By Radar.Ranges



Oneway Anova

Means for Oneway Anova

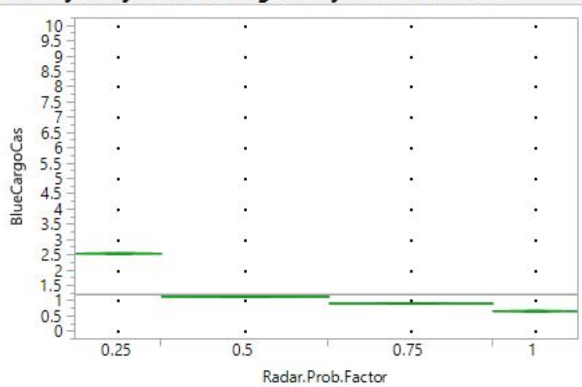
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
15	36960	7.51166	0.01832	7.4758	7.5476
30	70560	3.32874	0.01326	3.3028	3.3547
45	72240	3.27368	0.01310	3.2480	3.2994
60	36960	2.27468	0.01832	2.2388	2.3106

Std Error uses a pooled estimate of error variance

Radar’s detection range against the Red surface platform and incoming ASCM has significant effect on the outcome of the model if less than 30 NM.

Figure 33. Effects of radar ranges on response variables (expected casualties of cargo vessels).

Oneway Analysis of BlueCargoCas By Radar.Prob.Factor



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0.25	36960	2.57957	0.01285	2.5544	2.6048
0.5	72240	1.16653	0.00919	1.1485	1.1845
0.75	70560	0.94459	0.00930	0.9264	0.9628
1	36960	0.69286	0.01285	0.6677	0.7180

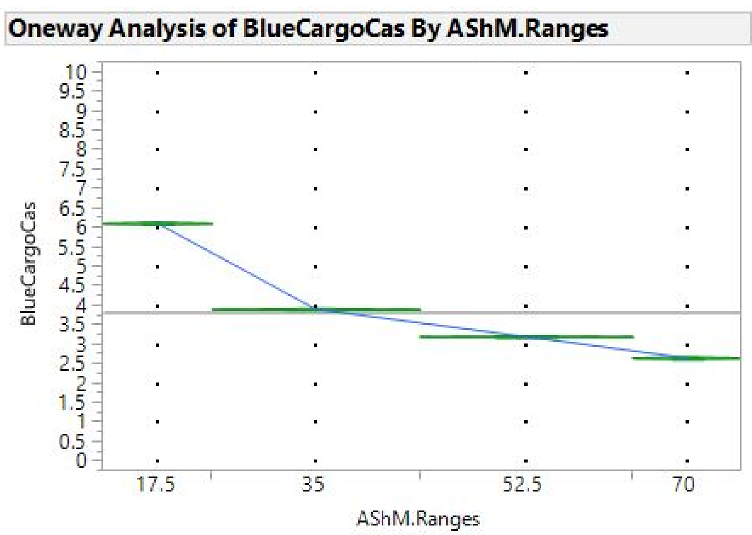
Std Error uses a pooled estimate of error variance

Change in radar probability of detection seems to have similar effect on the output of the model. Its impact is more significant below 50% of the original values and reduces gradually beyond 50%, having linear effect.

Figure 34. Effect of radar probability of detecting the incoming Red missile and surface ships on output of the model.

2. Surface-to-Air Missile/Anti-Missile Missile

Similar to radar, the range and SSKP of surface-to-air missiles were varied over four degradation levels as factors (0.25, 0.5, 0.75 and 1) of their maximum values mentioned in Chapter III. The range of Blue SAM is found to be the second most important factor after range of radar in determining the protection level of the convoy operations under a given threat. Its effect on the response variable is similar to that of radar detection range between 25% and 50% (17.5–35 NM) of its maximum range (70 NM) but then becomes much more linear when increased beyond 50% to 100% (35–70 NM). Every increment in SAM range reduces the expected losses of Blue cargo vessels and seems to have an exponential impact on the outcome of the model, as shown in Figure 35. It brings an overall improvement of about 230% when varied from 17.5 NM to 70 NM.



Oneway Anova

Means for Oneway Anova

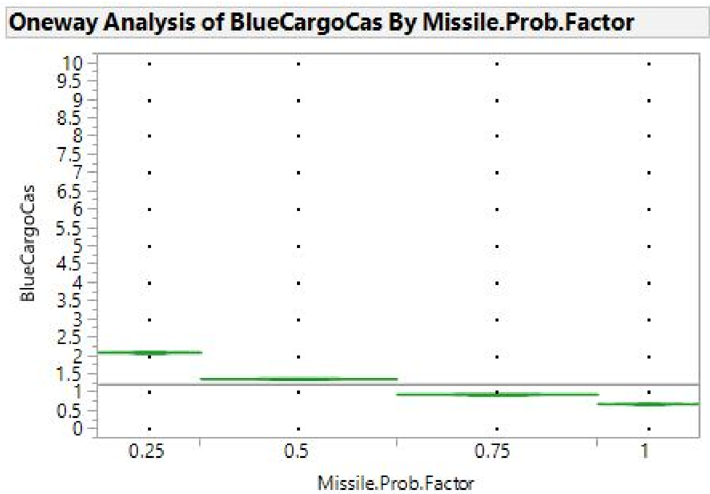
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
17.5	36960	6.12435	0.01950	6.0861	6.1626
35	70560	3.91702	0.01411	3.8894	3.9447
52.5	72240	3.21044	0.01395	3.1831	3.2378
70	36960	2.66253	0.01950	2.6243	2.7007

Std Error uses a pooled estimate of error variance

The expected casualties of Blue cargo vessels reduce exponentially with the increase in SAM range.

Figure 35. Effect of SAM range in determining the output of the model.

By keeping the SAM range constant and varying its SSKP, we found similar effect on the output as its range, as shown in Figure 36. An increase in SSKP of the SAM decreases the expected losses of Blue convoy by approximately 300% when its maximum values are varied from 25% to 100%. This suggests that SAM SSKP has a slight edge over its range, as the improvement was about 230% for the variation in range.



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0.25	36960	2.10733	0.01304	2.0818	2.1329
0.5	70560	1.39144	0.00944	1.3729	1.4099
0.75	72240	0.96534	0.00933	0.9471	0.9836
1	36960	0.70525	0.01304	0.6797	0.7308

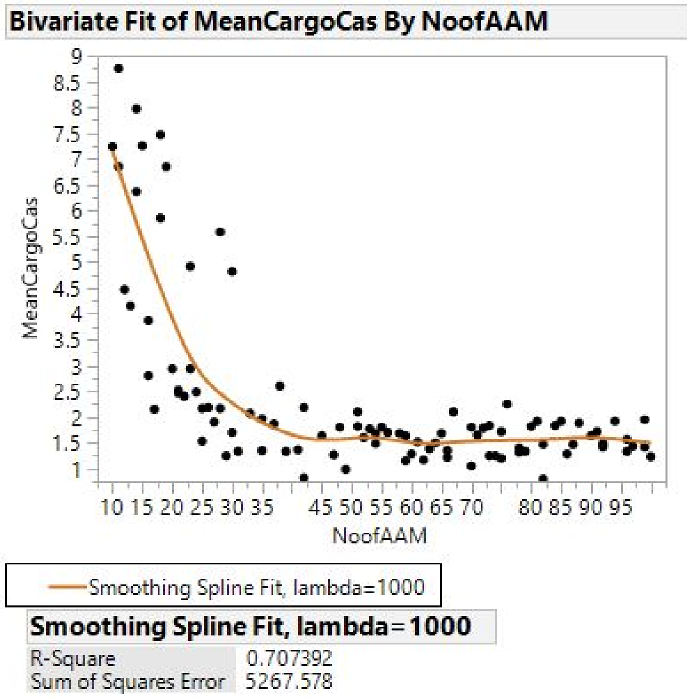
Std Error uses a pooled estimate of error variance

The Figure indicates that increase in SSKP of the ASCM decreases the expected casualties of Blue convoy as per exponential distribution.

Figure 36. Effect of variation in SSKP of the ASCM on outcome of the model.

3. Number of Surface-to-Air Missiles onboard Blue DDGs

The number of surface-to-air missiles onboard the Blue DDGs was varied from 10 to 100 to see if it had any significance in determining the output of the model. It was found that they are highly significant when less than 30. Its impact on the model decayed exponentially beyond that, as shown in Figure 37. It is therefore considered critical for the Blue DDGs to carry sufficient SAMs (30 in the given problem) against a perceived threat in order to provide effective protection to the convoy.



The expected casualties of Blue cargo vessels decrease exponentially with the increase in number of SAMs.

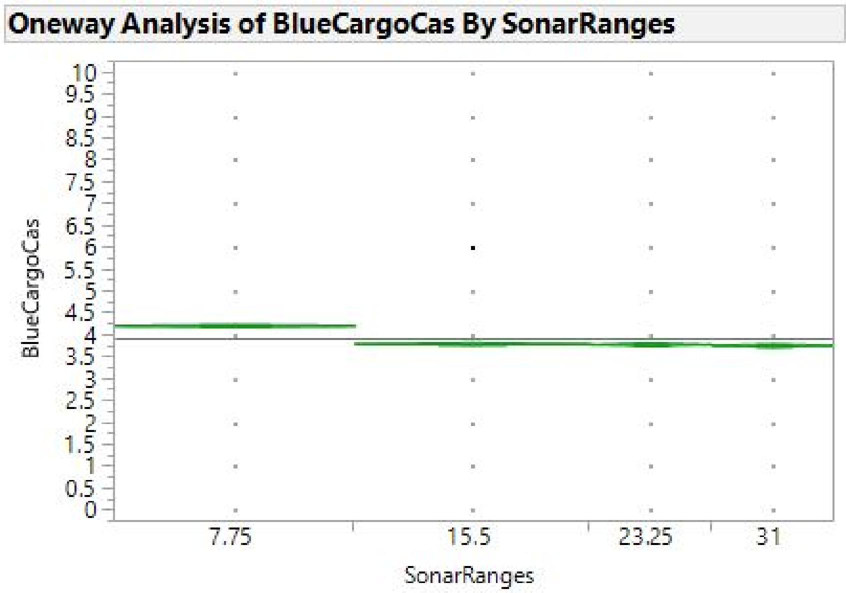
Figure 37. Effect of number of SAMs on the outcome of the model.

4. Sonar

The decision tree in Figure 28 does not show any significance of the range of sonar, but Figure 31 indicates that the probability of detection is highly significant. Both the regression models capture its significance. Additional analysis showed that the sonar range of Blue DDGs affects the model output when it is less than 15 Km, as seen in Figure 38. This, when tied to the maximum range of torpedoes of the DDGs (20 Km), seems quite intuitive. The sonar detection of a contact is only useful if the detection is followed by torpedo engagement, which implies a range of only up to 20 Km.

The impact of variation in sonar detection probability is much more significant than its range, as shown in Figure 39. The expected casualties of Blue convoy reduce more significantly with increase in the detection probability of the sonar than with its range especially, between 50% and 75% of its original values. This indicates that sonar

probability of detection is more significant than its range. The rate of reduction seems to be following half normal distribution as it reduces beyond a factor level of 0.75 to 1.



Oneway Anova

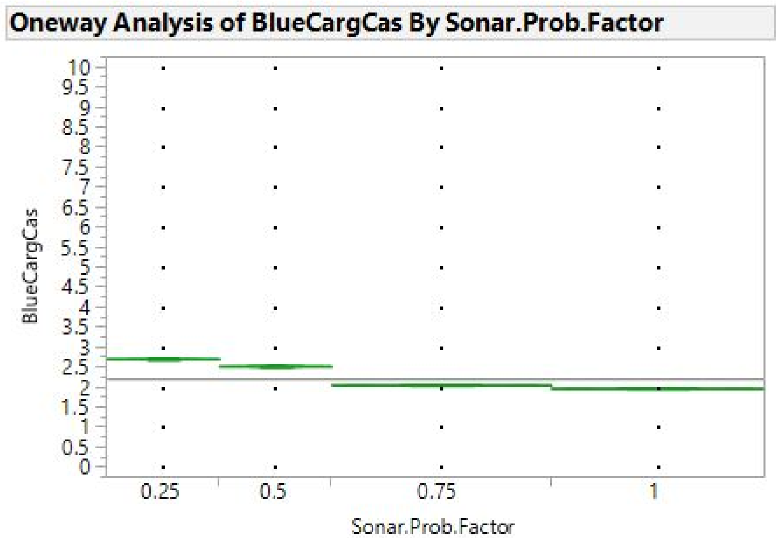
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
7.75	72240	4.23772	0.01486	4.2086	4.2668
15.5	70560	3.82618	0.01504	3.7967	3.8556
23.25	36960	3.81144	0.02078	3.7707	3.8522
31	36960	3.79034	0.02078	3.7496	3.8311

Std Error uses a pooled estimate of error variance

The sonar range is significant in determining the output of the model if it is less than 15 Km.

Figure 38. Effect of sonar ranges of Blue DDGs on the response variable.



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0.25	36960	2.72616	0.01550	2.6958	2.7565
0.5	36960	2.54702	0.01550	2.5166	2.5774
0.75	72240	2.07817	0.01109	2.0564	2.0999
1	70560	1.99195	0.01122	1.9700	2.0139

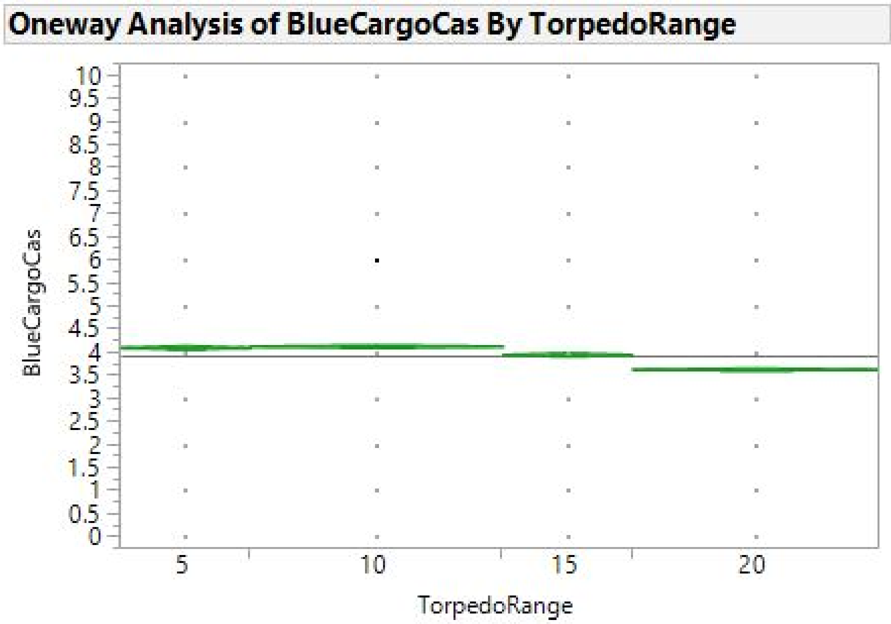
Std Error uses a pooled estimate of error variance

The figure indicates a linear relationship between the sonar probability factor and the response variables when it is less than 0.75 but decays gradually thereafter.

Figure 39. Effect of sonar probability of detection on the expected losses of Blue convoy.

5. Torpedo

The torpedo range of Blue DDGs seems to be insignificant until it is more than 10 Km, as shown in Figure 40. When increased beyond 10 Km, the torpedo range brings very steady improvement to the model as compared to other factors like radar detection and ASCM range. It is worth mentioning here that the maximum Blue DDG torpedo range is 20 Km, whereas that of the submarine is 25 Km and the Blue DDGs are stationed 4–5 NM (approximately 10 Km) away from the convoy. Therefore, the Blue DDG's torpedo range seems to be effective only if it is more than 10 Km, as this enables the Blue DDGs to fire on the Red submarine before it fires its torpedoes on the convoy.



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
5	36960	4.12430	0.02077	4.0836	4.1650
10	72240	4.15061	0.01486	4.1215	4.1797
15	36960	3.97806	0.02077	3.9373	4.0188
20	70560	3.65316	0.01503	3.6237	3.6826

Std Error uses a pooled estimate of error variance

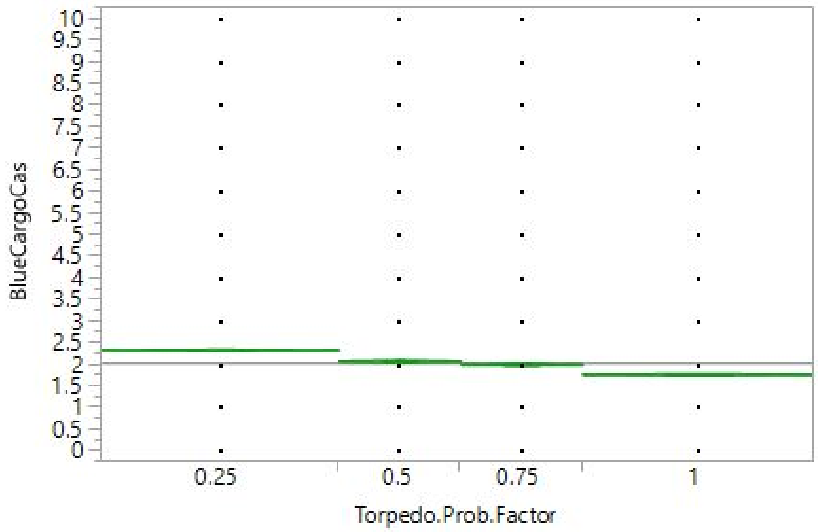
The torpedo range is insignificant in determining the output of the model until it is more than 10 Km. When increased beyond 10 Km, it brings very steady improvement to the output as compared to other factors of the model.

Figure 40. Effect of torpedo range of Blue DDGs on the output of the model.

The torpedo's SSKP is found to have more significant impact than its range on the expected hits on the convoy. Its impact seems to be approximately linear though less steep between factor levels of 0.5 to 0.75, as shown in Figure 41. This in turn suggests that torpedoes with long ranges and high SSKPs are preferred in antisubmarine warfare—an intuitive and confirming result.

Fit Group

Oneway Analysis of BlueCargoCas By Torpedo.Prob.Factor



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0.25	72240	2.34729	0.01083	2.3261	2.3685
0.5	36960	2.09751	0.01514	2.0678	2.1272
0.75	36960	2.02481	0.01514	1.9951	2.0545
1	70560	1.78231	0.01096	1.7608	1.8038

Std Error uses a pooled estimate of error variance

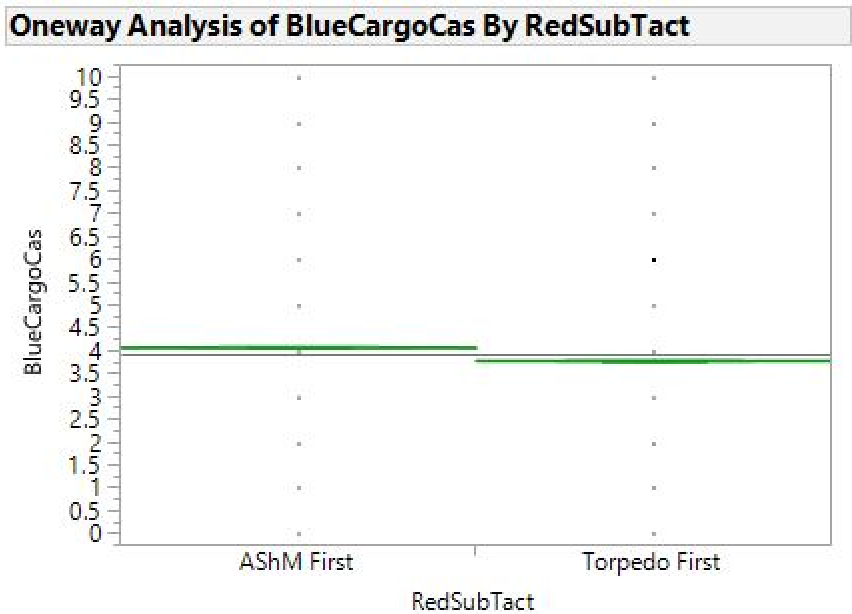
Torpedo SSKP seems to be insignificant when varied between 0.5 and 0.75 of the original values mentioned in Chapter III.

Figure 41. Effect of torpedo SSKP on the outcome of the model.

6. Weapon Employment Priority of Red Submarine

The Red submarine carries two types of weapons: ASCM and heavy weight torpedo. It may exercise approach and attack tactics based on its priority of weapon against the convoy ships, but each may have certain benefits and risks, which are discussed in Chapter III. The analysis shows that the convoy suffers more expected casualties when the Red submarine employs ASCM first and then closes it for carrying out torpedo attack, as shown in Figure 42. It is worth highlighting, however, that the Red submarines fire five fewer torpedoes overall when they employ ASCM as priority weapon (Figure 43). Additionally, a torpedo is considered to be more lethal than ASCM in naval warfare, whereas this study considers their lethality to be equal due to MANA

limitations. Therefore, this area needs further exploration by simulating the model in other simulation software, as MANA cannot assign different sustainability to a platform against different weapons.



Oneway Anova

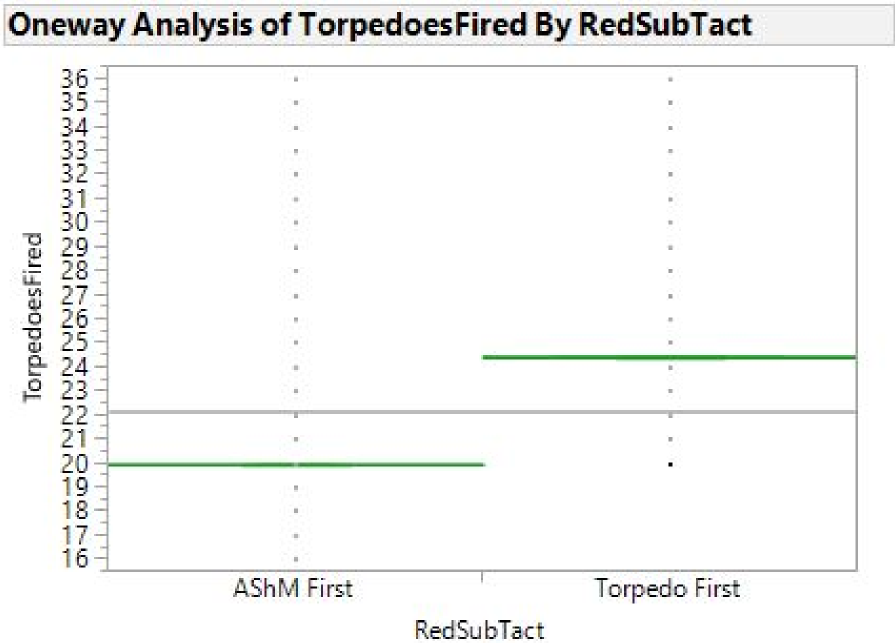
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
AShM First	108360	4.10171	0.01214	4.0779	4.1255
Torpedo First	108360	3.80776	0.01214	3.7840	3.8316

Std Error uses a pooled estimate of error variance

The Blue convoy suffers more casualties when the Red submarine chooses ASCM as priority weapon.

Figure 42. Expected casualties of Blue cargo vessels vs Red submarine weapon employment priority.



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
AShM First	108360	19.9656	0.01375	19.939	19.993
Torpedo First	108360	24.4375	0.01375	24.411	24.464

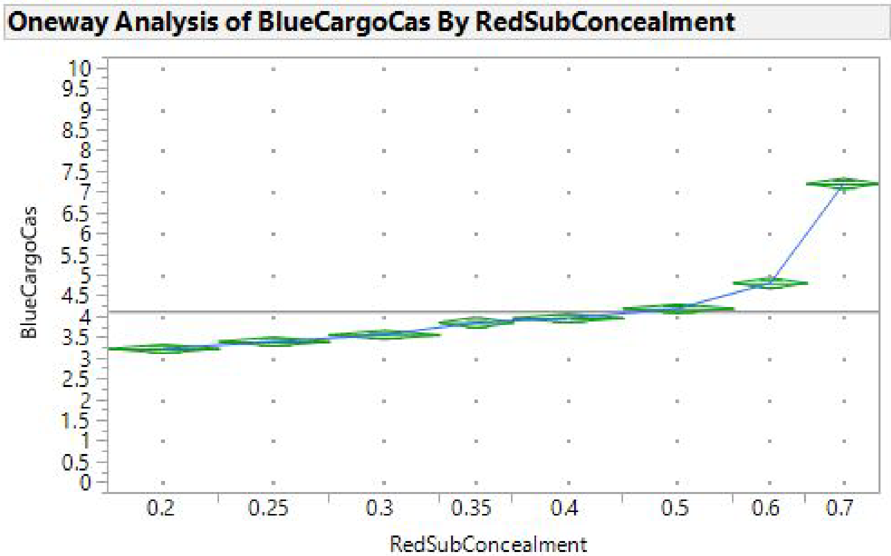
Std Error uses a pooled estimate of error variance

The Red submarine fires five fewer torpedoes when employing ASCM as its priority weapon than when it is torpedo.

Figure 43. Torpedoes fired by the Red submarines in different tactics of weapon priority.

7. Red Submarine Concealment

The Red submarine's "concealment" is related to its quietness and the ocean's acoustic environment. We varied it from 0.2 to 0.7 to see how this could affect the tactics of convoy protection. The results suggest that expected Blue convoy casualties increase exponentially with the increase in concealment factor of the Red submarine, as shown in Figure 44.



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0.2	5040	3.25575	0.05481	3.1483	3.3632
0.25	5040	3.42837	0.05481	3.3209	3.5358
0.3	5040	3.58948	0.05481	3.4821	3.6969
0.35	3360	3.88780	0.06713	3.7562	4.0194
0.4	5040	3.99464	0.05481	3.8872	4.1021
0.5	5040	4.22619	0.05481	4.1188	4.3336
0.6	3360	4.83601	0.06713	4.7044	4.9676
0.7	3360	7.23601	0.06713	7.1044	7.3676

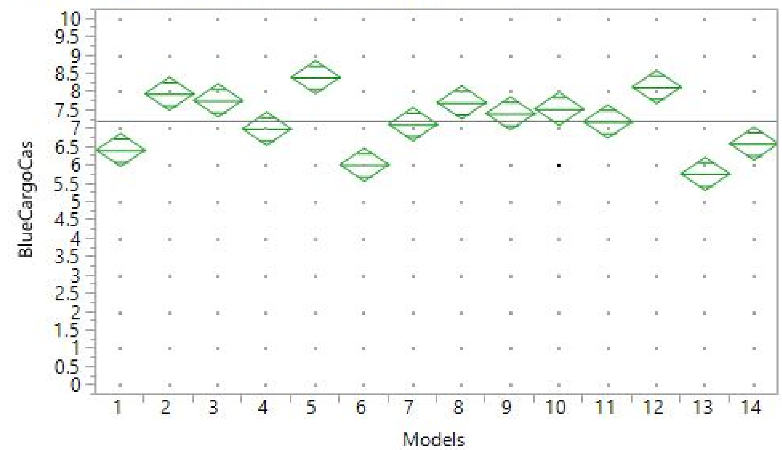
Std Error uses a pooled estimate of error variance

The losses suffered by the Blue convoy seem to increase exponentially with the increase in concealment of the Red submarine.

Figure 44. Effect of submarine concealment on expected casualties of Blue cargo vessels.

This is of serious concern for Blue when deciding which model needs to be employed in a specific oceanographic environment and/or against quieter submarines. Analysis of the results shows that models 6 (5 DDGs in the inner screen, 2 MDUSVs along with 2 DDGs in the outer screen) and 13 (model 6 + 2 TERNs) perform better in a situation when the acoustic conditions are unknown, as shown in Figure 45. It also takes the combined effect of submarine’s weapon employment tactics. Interestingly, models 4 and 5 lose their effectiveness against a quieter submarine and/or in difficult acoustic environments, which were found to be the best defensive options against the two weapon employment tactics of the Red submarine.

Oneway Analysis of BlueCargoCas By Models



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	168	6.43750	0.22953	5.9875	6.8875
2	168	7.97083	0.22953	7.5208	8.4209
3	168	7.78750	0.22953	7.3375	8.2375
4	168	7.01667	0.22953	6.5666	7.4667
5	168	8.42083	0.22953	7.9708	8.8709
6	168	6.03750	0.22953	5.5875	6.4875
7	168	7.14167	0.22953	6.6916	7.5917
8	168	7.73333	0.22953	7.2833	8.1834
9	168	7.43333	0.22953	6.9833	7.8834
10	168	7.55833	0.22953	7.1083	8.0084
11	168	7.21250	0.22953	6.7625	7.6625
12	168	8.15417	0.22953	7.7041	8.6042
13	168	5.78750	0.22953	5.3375	6.2375
14	168	6.61250	0.22953	6.1625	7.0625

Std Error uses a pooled estimate of error variance

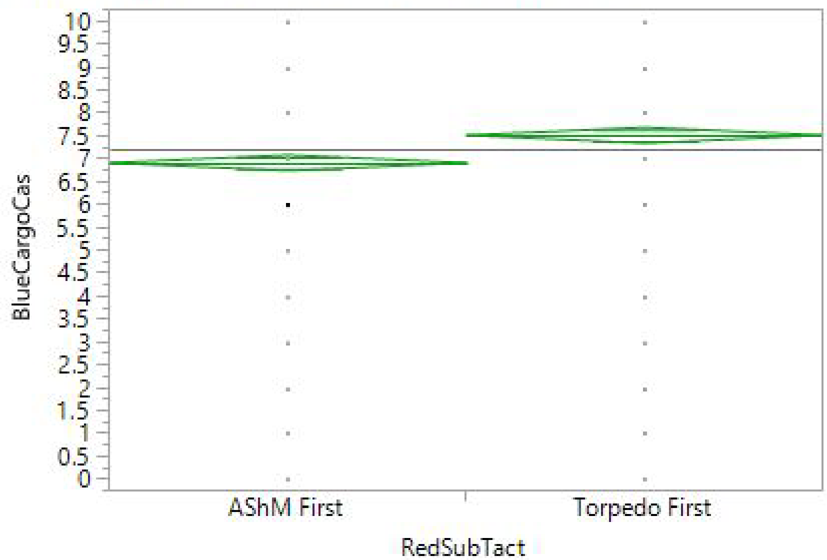
Weight RedSubConc0.7

No Weight Rows 213360

Figure 45. Performance of the models against the highest Red submarine concealment: Models 6 and 13 perform better when the Red submarine is quieter and/or the ocean's acoustic environment is difficult for detecting a submarine.

Notably, the priority of weapon employment by the Red submarine shifts from ASCM to torpedo if it is quieter and/or in difficult acoustic environment. Figure 46 shows that the Blue convoy suffers more losses when the Red submarine chooses torpedo as its priority weapon under the mentioned considerations. This makes sense, as a quieter submarine and/or difficult acoustic conditions make a torpedo approach to the convoy less risky and therefore a higher probability of successful attack and evasion to also execute a missile attack.

Oneway Analysis of BlueCargoCas By RedSubTact



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
AShM First	1176	6.93452	0.08826	6.7615	7.1076
Torpedo First	1176	7.53750	0.08826	7.3645	7.7105

Std Error uses a pooled estimate of error variance

Weight RedSubConc0.7

Figure 46. Effect of submarine priority of weapon employment on the expected Blue convoy losses: The submarine should prefer employing torpedo as priority weapon if it is quieter and/or in difficult acoustic environment.

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VI. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

The close escort model outperformed the zone defense model across all variations in our study. In the convoy size of 10, expected casualties of cargo ships were 3.95 [3.938, 3.972] in the close escort model and 7.35 [7.317, 7.382] in the zone defense model, which indicates that the close escort model is almost twice as effective as the zone defense model. Out of 14 models of the close escort models, the model with two ASW helicopters in the intermediate screen and five DDGs in the close escort role conceded minimum expected losses (2.62 [2.54, 2.71]) of the convoy to the Red forces when the weapon employment priority for Red submarine was torpedo. The same model is considered to be effective against a Red submarine having torpedo as the only weapon. This model, however, was almost ineffective against the second tactic (ASCM as priority weapon) of the Red submarine. The models having helicopters or MDUSVs in the outer screen are found to be more effective against such threat.

The convoy suffers most of its losses from Red submarines instead of Red surface combatants. Therefore, one expects an adversary will employ more submarines than surface ships against the convoy. The TERNs are used in ISR mode, which adds to Blue capabilities in finding Red DDGs but has no effect against finding Red submarines. Additionally, the Blue ASCM range is restricted to 60 NM, so the additional information provided by TERNs about Red DDGs will require the dispatched Blue DDGs to go closer and engage them, pulling them away from the primary submarine threat. Therefore, TERNs' inclusions in the model did not bring much improvement to overall defense effectiveness. Their usefulness will become apparent if Blue DDGs are provided with longer-range ASCM, however, which they can launch in third party targeting technique. Also, other organic platforms like helicopters with air-to-surface missile (ASM) can be dispatched for engagement of the Red DDGs once they are located by a TERN. MDUSVs with TALON were found to be useful alternatives to ASW helicopters if they are provided sufficient defense against the ASCM (two DDGs in our study) and deployed in intermediate or outer screen.

Sensitivity analysis on various factors including ranges and accuracies of weapons and sensors was carried out. Overall sensor range and performance were considered more important in the models than the weapons. This seems quite intuitive as the weapons firing is tied to the performance of the sensors. A weapon can only be fired on target if the target is detected and classified by the weapon's associated sensor. Air defense factors (radar ranges, SAMs and number of SAMs on each platform) were found to be more critical if they were not capable enough to counter the ASCM threat. Underwater defense factors (sonar and torpedo capabilities) were also significant but to a much lesser degree. They were comparable to air defense factors if the minimum requirement of air defense is met, however. The difference in their significance is perceived to be due to the amount of threat posed by the ASCM (number of ASCMs) as compared to the torpedo. For effective protection of convoy against a multidimensional threat, the weapon and sensor requirements of Blue surface combatants can be generalized as follows.

- Long-range radars with above average detection probabilities.
- Medium-range SAMs or anti-missile missiles with high SSKP.
- Sufficient number of SAMs per DDG depending upon the perceived threat.
- Long-range torpedoes with high SSKP.
- Sonars having comparable range to torpedoes and with above average detection probabilities.

The Red submarines were more effective with ASCM as their weapon priority for employment against the Blue convoy in easy acoustic conditions, though tough acoustic conditions favored torpedo employment first. There was a very small but significant difference between the outcomes of the two weapon employment tactics. It was found, however, that the submarines fired five fewer torpedoes when employing ASCM as priority weapon. One needs to consider that a torpedo hit is more effective than an ASCM hit, which we could not simulate because of the MANA limitations. Submarine concealment factor, indicating its quietness and/or various acoustic conditions, was also analyzed in sensitivity analysis. It was found that the models having two MDUSVs along with two DDGs in the outer screen and five DDGs in the inner screen were more robust

and effective against quieter submarines and/or in difficult acoustic conditions. The models containing ASW helicopters were outperformed by those in which they were replaced by MDUSVs when the convoy was faced with a threat comprising quieter submarines and/or in difficult acoustic conditions. The Red submarine was also found to be better off employing torpedo as priority weapon instead of ASCM in such conditions.

B. RECOMMENDATIONS

Based upon the discussion above, the following is recommended for the Blue force.

1. Concentrate forces around the convoy: use close escort model instead of zone defense model.

2. If sufficient platforms are available for the convoy operation, use layered defense in sector screen formation.

3. ASW helicopters are better platforms in moderate acoustic environments and may be used against SSNs that are less quiet.

4. If available, use MDUSVs with TALON (with radar system) in ASW role in the forward screen. MDUSVs may be preferred over ASW helicopters if the acoustic environment is tough or the enemy has employed quieter submarine (SSKs) for attacking the convoy. MDUSVs should be employed in combination with surface platforms to provide them defense against the ASCMs, however.

5. In the case of layered defense, intermediate screens are preferred over outer screens if the Red submarine is capable of torpedo attack only. In an uncertain situation, outer screen is the desired forward layer of defense.

6. Detection of Red surface threat and ASCMs at long ranges is particularly important for convoy protection in a multi-dimension threat environment. Additional resources may be deployed for their detection if the performance of onboard radars is degraded. The same is recommended if the enemy has employed stealthier surface platforms or is using sea skimming ASCMs.

7. Neutralization of the enemy surface platforms carries significant importance. Therefore, surface combatants should be equipped with ASCMs having range advantage (or at least range parity) over those of Red.

8. Use strong and sufficient anti-air defense when faced with a threat of ASCM along with subsurface threat.

9. If capable of launching long-range ASCMs in addition to torpedoes, the Red submarine should prefer to attack with missile first and then close the convoy for torpedo attack in a moderate or good acoustic environment. Quieter submarines like SSKs or SSNs in tough acoustic environments should prefer torpedo as priority weapon, however. This factor needs further exploration, though, as this recommendation assumes equal lethality of the two weapons against the convoy.

10. Long-range torpedoes and comparable range sonars with above average detection probabilities and high SSKP, respectively, may be the preferred options for ASW operations.

C. FUTURE WORK

The study uses Map Awareness Non-Uniform Automata (MANA) simulation software platform. MANA is a good platform to simulate less detailed combat models in short time frames, but it was limited in simulating a few aspects of our model. These are highlighted here for further exploration in future studies.

MANA's main board is limited to 540 × 540 NM, which may not cover the whole battlefield for a particular scenario.

MANA is unable to assign dynamic waypoints to agents, so tactical maneuvers of the convoy cannot be simulated. This may have significant impact on the outcome of the model. Alternate simulation software (OSM) may be used for simulating the model but with the additional factor of tactical maneuver.

MANA is also incapable of assigning different lethality to different weapons against the same target (effectiveness of torpedo and missile against surface targets). This is considered to be an important factor in deciding upon the weapon employment tactic of the Red submarine as there was very little but significant advantage to ASCM over torpedo's employment as priority weapon. Therefore, this needs to be further explored by simulating the model on a different simulation platform like OSM.

Other roles of TERN including armed reconnaissance with ASCM or torpedo may be exploited to find out its best employment tactic in the model.

Other tactics may be explored for weapon delivery against the Red surface platforms when they are detected by TERN. Use of long-range ASCM with third party

targeting technique and helicopters with ASM may be among the feasible options to consider.

The study is based on unclassified data of USN platforms as Blue force and PLAN platforms as Red force. Additionally, it uses a hypothetical scenario on the open sea with a specific number of Red DDGs and submarines. Analysis of a particular scenario may require rerunning the model with more accurate (classified) data of the two forces.

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APPENDIX. NOLH DESIGN SPREADSHEET OUTPUT

As mentioned in Chapter III, the total design points of the study are 4644 × 2 (9288) when the NOLH output is crossed with the scenarios and the two weapon employment tactics of the Red submarine. For simplicity, we only present the NOLH output for the understanding of the reader.

Submarine Concealment	Missile Range/Prob. multiplier	Torpedo Range/Prob. multiplier	Radar Range/Prob. multiplier	Sonar Range/Prob. multiplier	No. Anti-Air Missiles
0.32	0.5	0.5	0.5	0.5	72
0.65	0.5	0.5	0.5	0.25	51
0.42	0.75	0.25	0.5	0.5	24
0.55	1	0.5	0.5	0.5	78
0.2	0.5	0.75	0.5	0.25	58
0.55	0.5	0.75	0.25	0.5	40
0.4	1	0.75	0.5	0.25	30
0.49	0.75	1	0.25	0.5	93
0.21	0.25	0.5	0.5	0.5	98
0.69	0.25	0.5	0.5	0.25	19
0.22	1	0.5	0.5	0.5	16
0.66	1	0.5	0.5	0.25	100
0.44	0.5	1	0.5	0.5	75
0.58	0.5	1	0.5	0.25	31
0.33	0.75	1	0.5	0.5	29
0.59	0.75	1	0.25	0.5	56
0.31	0.5	0.5	0.75	0.25	73
0.68	0.5	0.5	0.75	0.5	28
0.29	0.75	0.5	0.75	0.5	13
0.52	1	0.5	0.75	0.25	82
0.34	0.5	0.75	1	0.5	70
0.51	0.5	0.75	1	0.5	21
0.3	0.75	0.75	1	0.5	41
0.57	0.75	1	1	0.5	66
0.34	0.5	0.5	0.75	0.5	99
0.67	0.25	0.5	0.75	0.25	36
0.32	0.75	0.5	1	0.25	21
0.7	1	0.5	0.75	0.25	78
0.34	0.5	0.75	0.75	0.5	59
0.52	0.5	1	0.75	0.5	48

Submarine Concealment	Missile Range/Prob. multiplier	Torpedo Range/Prob. multiplier	Radar Range/Prob. multiplier	Sonar Range/Prob. multiplier	No. Anti-Air Missiles
0.43	0.75	0.75	0.75	0.25	45
0.47	0.75	1	1	0.25	76
0.24	0.5	0.5	0.5	0.75	54
0.63	0.5	0.25	0.25	0.75	46
0.38	1	0.25	0.5	0.75	23
0.46	1	0.25	0.5	0.75	96
0.23	0.5	0.75	0.25	0.75	85
0.62	0.25	0.75	0.5	1	37
0.36	1	1	0.25	0.75	15
0.63	1	1	0.5	1	87
0.36	0.5	0.25	0.5	0.75	71
0.61	0.5	0.5	0.25	0.75	57
0.45	0.75	0.5	0.5	0.75	35
0.51	0.75	0.25	0.25	0.75	77
0.31	0.25	0.75	0.5	0.75	61
0.64	0.5	0.75	0.25	0.75	11
0.22	0.75	0.75	0.5	0.75	22
0.49	1	0.75	0.5	1	80
0.43	0.5	0.5	1	0.75	96
0.61	0.25	0.25	0.75	0.75	47
0.4	0.75	0.5	0.75	0.75	26
0.66	0.75	0.25	1	0.75	60
0.36	0.5	0.75	0.75	1	85
0.63	0.25	1	0.75	1	18
0.3	0.75	0.75	0.75	1	16
0.64	1	0.75	0.75	1	66
0.28	0.25	0.5	0.75	0.75	68
0.53	0.5	0.25	1	0.75	27
0.25	1	0.5	1	1	42
0.5	0.75	0.5	1	0.75	92
0.41	0.5	1	0.75	0.75	90
0.48	0.25	0.75	0.75	0.75	43
0.37	0.75	1	1	0.75	47
0.65	0.75	0.75	1	1	61
0.45	0.75	0.75	0.75	0.75	55
0.58	0.75	0.75	0.75	0.75	38
0.25	0.75	0.75	0.75	1	59
0.48	0.5	1	0.75	0.75	86
0.35	0.25	0.75	0.75	0.75	32
0.7	0.75	0.5	0.75	1	52
0.35	0.75	0.5	1	0.75	70

Submarine Concealment	Missile Range/Prob. multiplier	Torpedo Range/Prob. multiplier	Radar Range/Prob. multiplier	Sonar Range/Prob. multiplier	No. Anti-Air Missiles
0.5	0.25	0.5	0.75	1	80
0.41	0.5	0.25	1	0.75	17
0.69	1	0.75	0.75	0.75	12
0.21	1	0.75	0.75	1	91
0.68	0.25	0.75	0.75	0.75	94
0.24	0.25	0.75	0.75	1	10
0.46	0.75	0.25	0.75	0.75	35
0.33	0.75	0.25	0.75	1	79
0.57	0.5	0.25	0.75	0.75	81
0.31	0.5	0.25	1	0.75	54
0.59	0.75	0.75	0.5	1	37
0.22	0.75	0.75	0.5	0.75	82
0.61	0.5	0.75	0.5	0.75	97
0.38	0.25	0.75	0.5	1	28
0.56	0.75	0.5	0.25	0.75	40
0.39	0.75	0.5	0.25	0.75	89
0.6	0.5	0.5	0.25	0.75	69
0.33	0.5	0.25	0.25	0.75	44
0.56	0.75	0.75	0.5	0.75	11
0.23	1	0.75	0.5	1	74
0.58	0.5	0.75	0.25	1	89
0.2	0.25	0.75	0.5	1	33
0.56	0.75	0.5	0.5	0.75	51
0.38	0.75	0.25	0.5	0.75	62
0.47	0.5	0.5	0.5	1	65
0.43	0.5	0.25	0.25	1	34
0.66	0.75	0.75	0.75	0.5	56
0.27	0.75	1	1	0.5	64
0.52	0.25	1	0.75	0.5	87
0.44	0.25	1	0.75	0.5	14
0.67	0.75	0.5	1	0.5	25
0.28	1	0.5	0.75	0.25	73
0.54	0.25	0.25	1	0.5	95
0.27	0.25	0.25	0.75	0.25	23
0.54	0.75	1	0.75	0.5	39
0.29	0.75	0.75	1	0.5	53
0.45	0.5	0.75	0.75	0.5	75
0.39	0.5	1	1	0.5	33
0.59	1	0.5	0.75	0.5	49
0.26	0.75	0.5	1	0.5	99
0.68	0.5	0.5	0.75	0.5	88

Submarine Concealment	Missile Range/Prob. multiplier	Torpedo Range/Prob. multiplier	Radar Range/Prob. multiplier	Sonar Range/Prob. multiplier	No. Anti-Air Missiles
0.41	0.25	0.5	0.75	0.25	30
0.47	0.75	0.75	0.25	0.5	14
0.29	1	1	0.5	0.5	63
0.5	0.5	0.75	0.5	0.5	84
0.24	0.5	1	0.25	0.5	50
0.54	0.75	0.5	0.5	0.25	25
0.27	1	0.25	0.5	0.25	92
0.6	0.5	0.5	0.5	0.25	94
0.26	0.25	0.5	0.5	0.25	44
0.62	1	0.75	0.5	0.5	42
0.37	0.75	1	0.25	0.5	83
0.65	0.25	0.75	0.25	0.25	68
0.4	0.5	0.75	0.25	0.5	18
0.49	0.75	0.25	0.5	0.5	20
0.42	1	0.5	0.5	0.5	67
0.53	0.5	0.25	0.25	0.5	63
0.25	0.5	0.5	0.25	0.25	49

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